Commissioning and Performance of the Outer Tracker Detector of the LHCb Experiment

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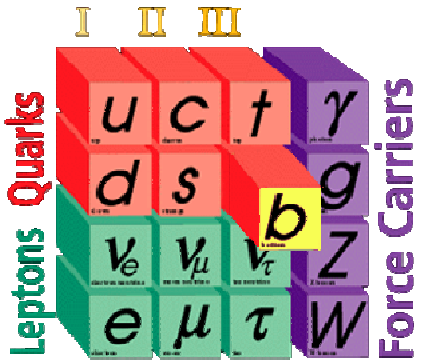
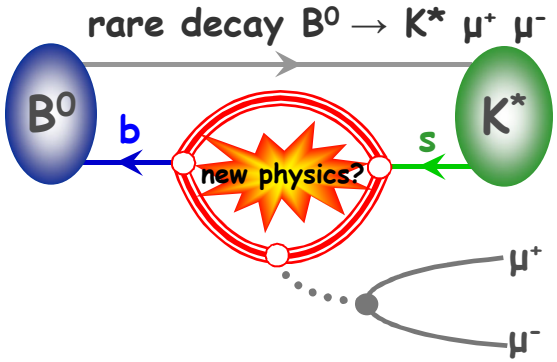
- Introduction
  - ✓ CP Violation and B Physics
  - ✓ the LHC environment for B Physics
  - ✓ the LHCb Experiment
- The LHCb Tracking System
  - ❖ overview (Inner and Outer Tracker)
  - ❖ expected performance
- The Outer Tracker
  - ❖ design and construction
  - ❖ (beam tests)
  - ❖ installation and commissioning

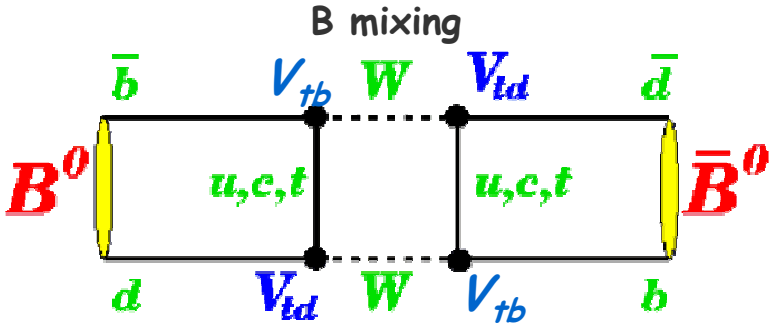
B Physics Mission



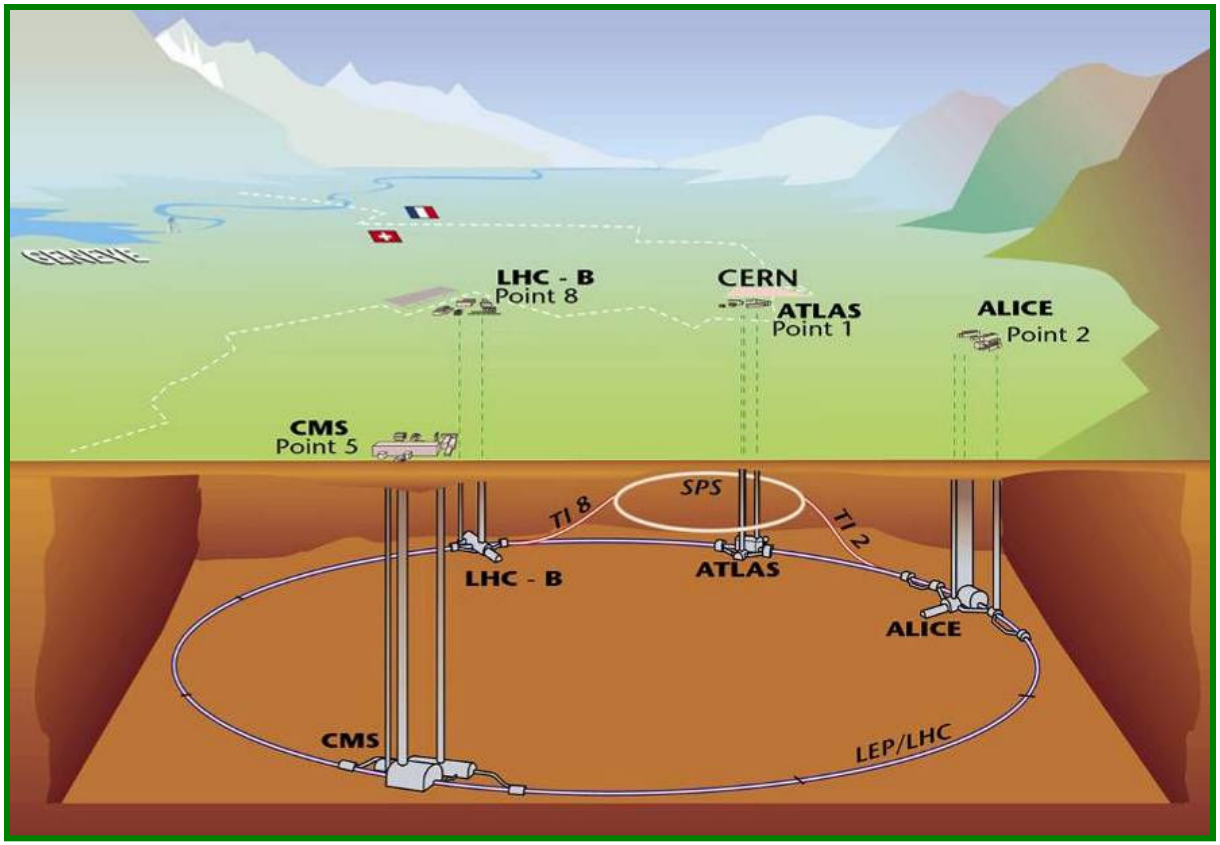
- The physics of hadrons containing b-quarks
- CP-violation (Charge-Parity asymmetry) with B-mesons
  - measurable through B/anti-B mixing and decay
- New physics with rare B decays
  - B decays with small conventional
  - branching fractions involving loop diagrams
  - New physics may contribute at the
  - same scale as conventional physics

Nobel prize 2008:
1. spontaneous symmetry breaking +
2. at least three families of quarks
   = possible *CP violation*





B Physics at the LHC



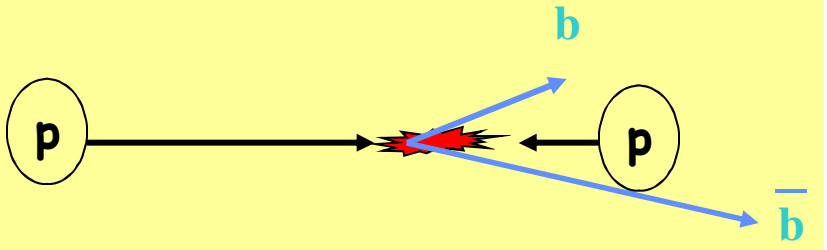
LHC will act as a prolific B-factory!

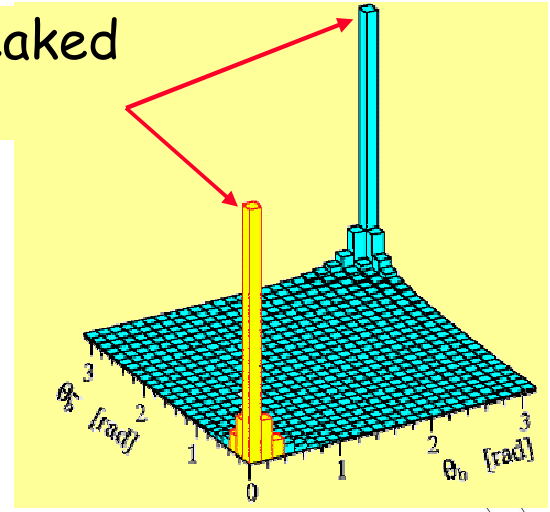
E.g. pp collisions at $\sqrt{s}$ = 14 TeV expected to give large b cross section $\sigma_{b\bar{b}}$ ~ 500 μb

- ATLAS, CMS: general-purpose experiment, including a B-physics program
- LHCb: dedicated B-physics detector, with PID, excellent decay-time resolution and efficient B trigger, running at "modest" luminosity $\mathcal{L} \sim 2 \times 10^{32}$ cm^{-2}s^{-1} (by adjusting beam focus) → **10^{12} $b\bar{b}$/year (10^{7} sec)**

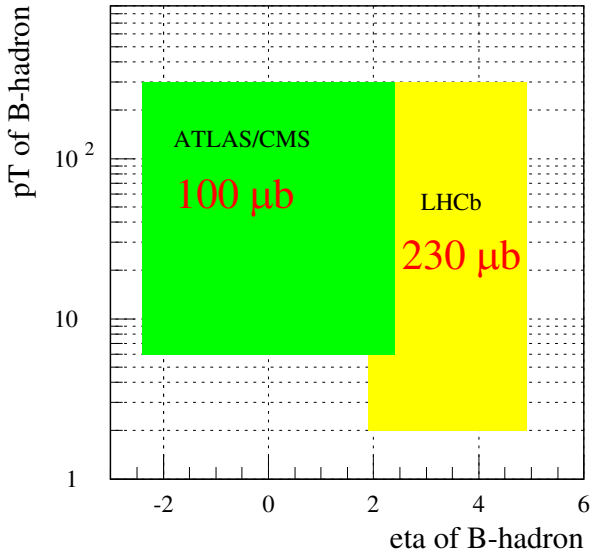
B Production at LHCb

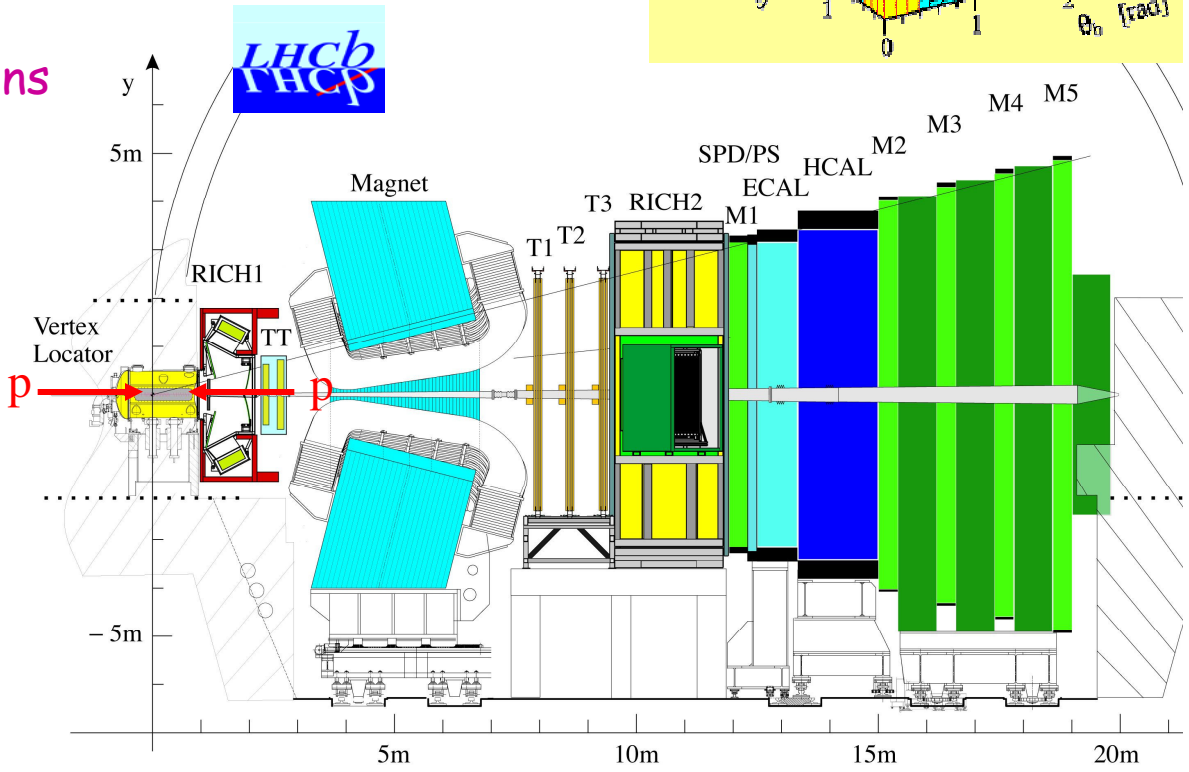
b hadrons production at LHC forward/backward peaked
⇒ LHCb forward spectrometer (10-300 mrad)





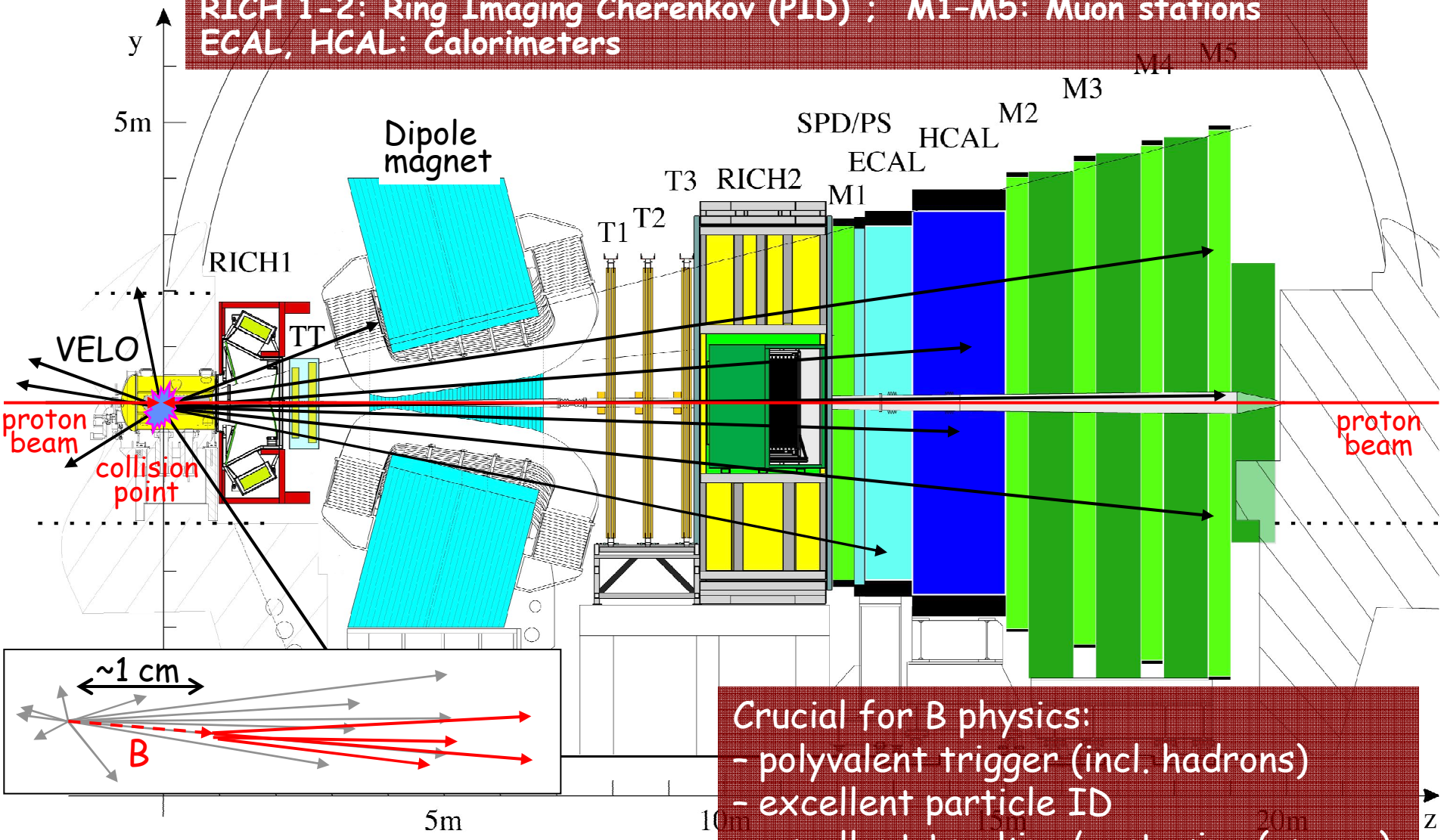
p_T *vs* η for detected B hadrons





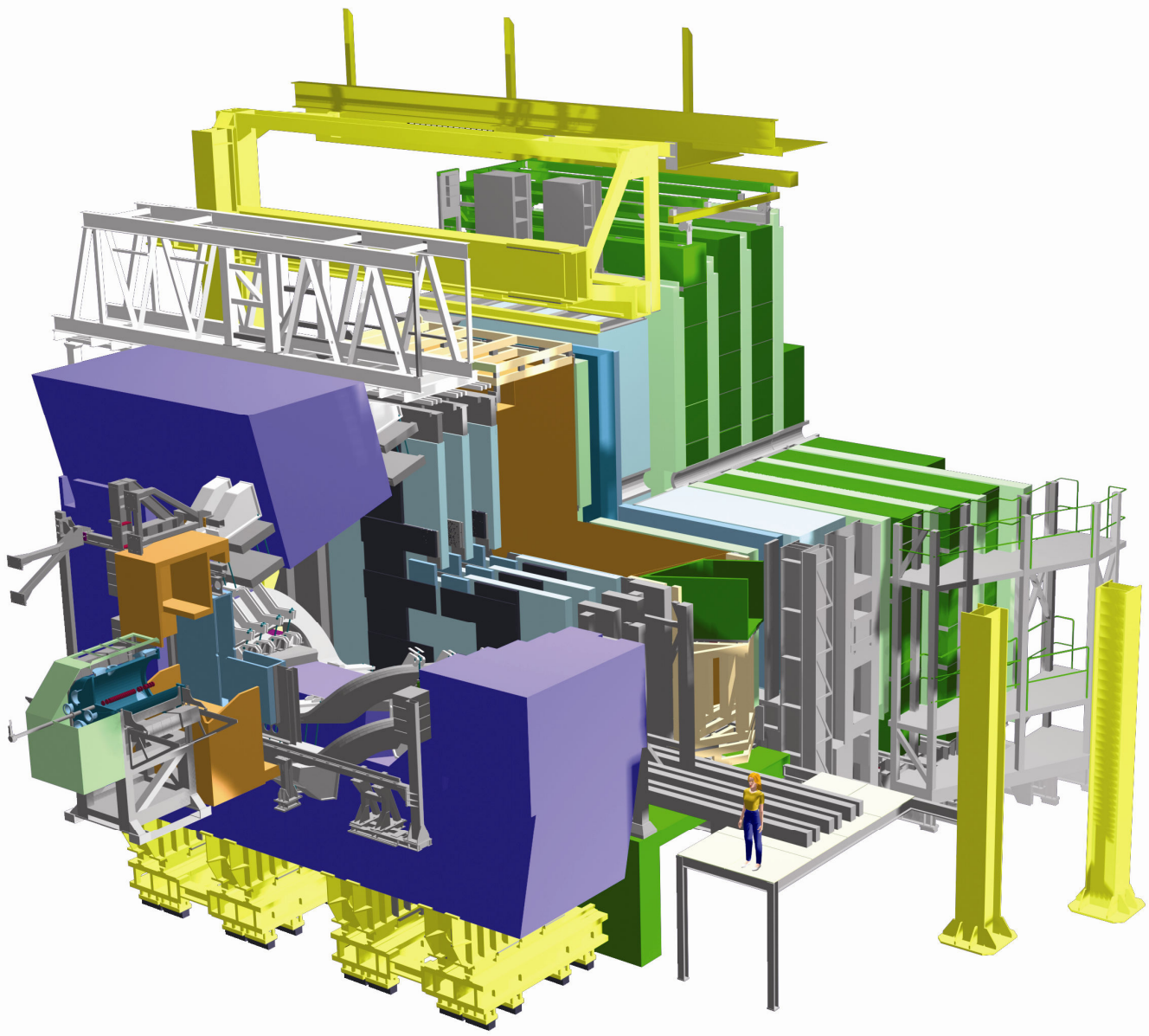
LHCb Detector (Overview)

VELO: Vertex Locator (around IP) ; TT, T1, T2, T3: Tracking stations
RICH 1-2: Ring Imaging Cherenkov (PID) ; M1-M5: Muon stations
ECAL, HCAL: Calorimeters



Crucial for B physics:
- polyvalent trigger (incl. hadrons)
- excellent particle ID
- excellent tracking/vertexing (σm, $\sigma\tau$)

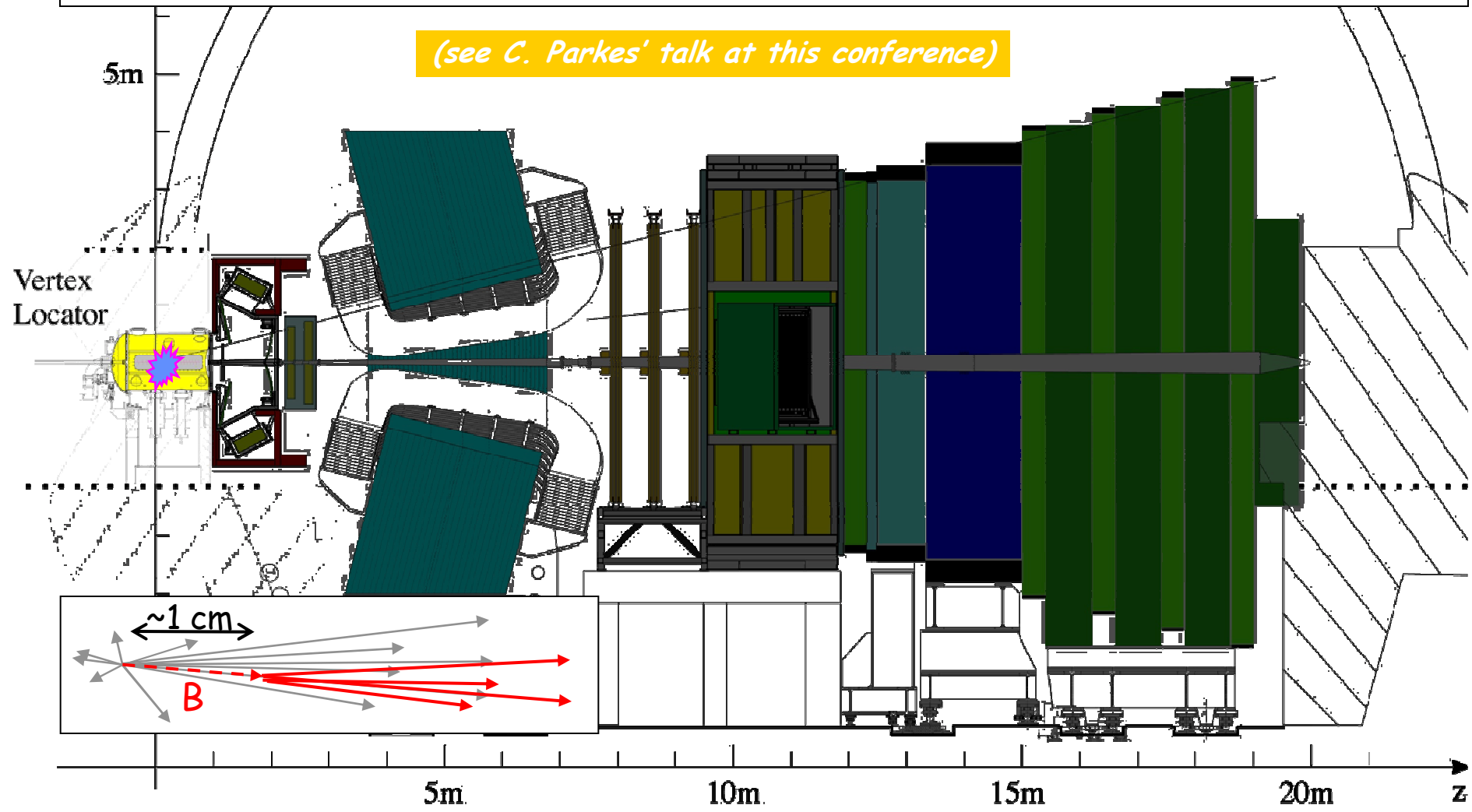
The LHCb Experiment (3D)



LHCb Detector Slide Show (1)

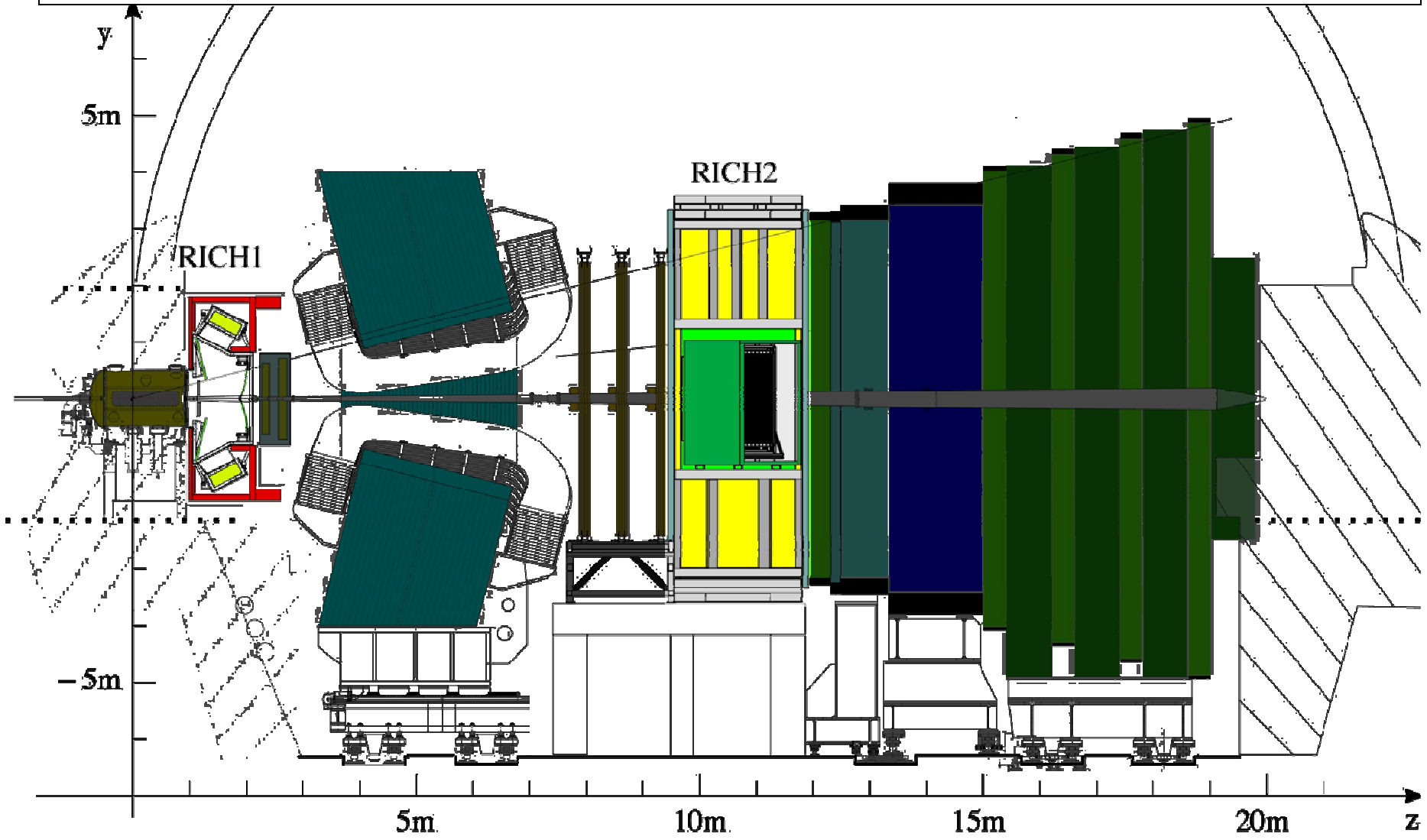
- contains the pp-collision point
- precise determination of primary and secondary vertices (B lifetime)

(see C. Parkes' talk at this conference)



LHCb Detector Slide Show (2)

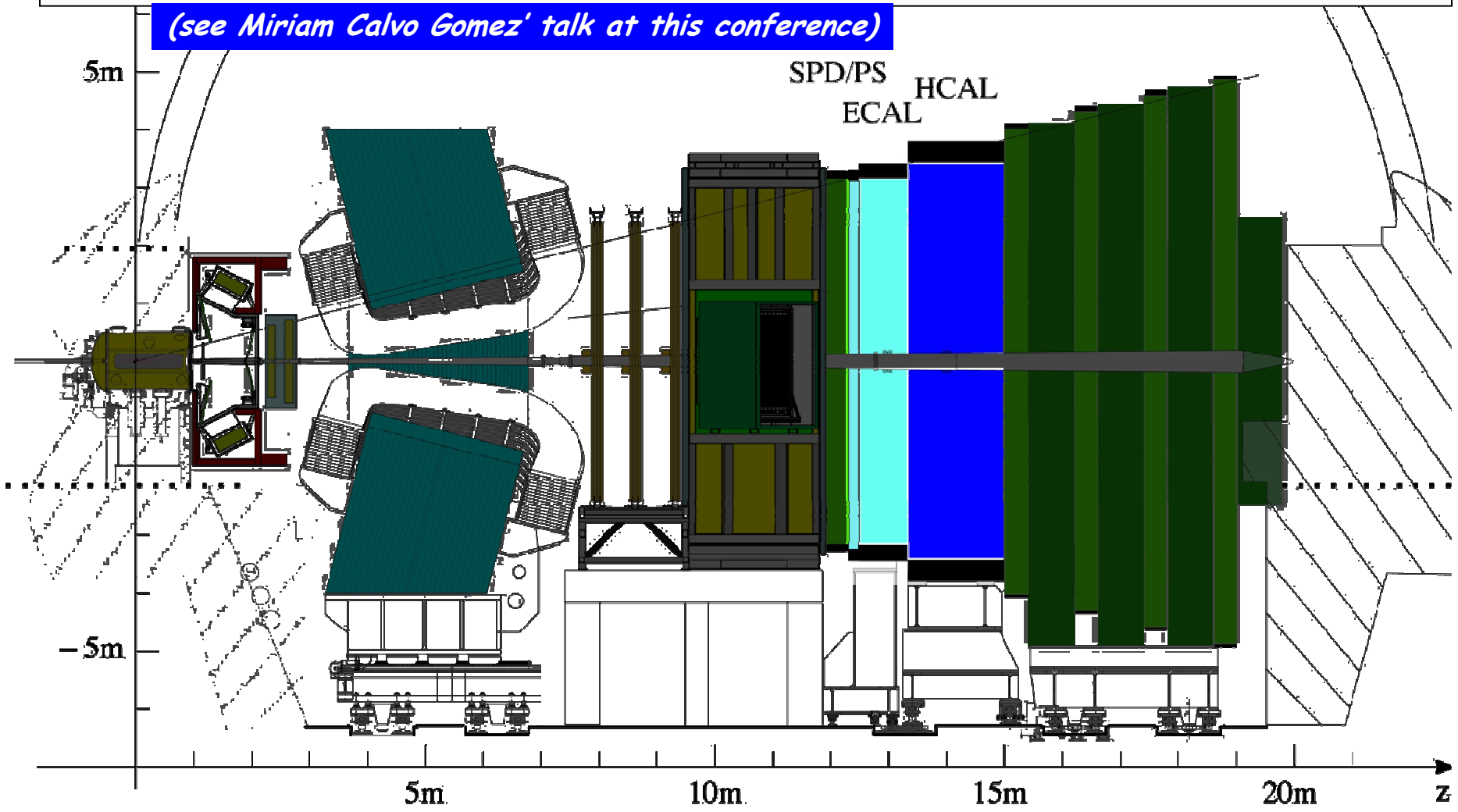
- Particle IDentification; kaon-pion separation



LHCb Detector Slide Show (3)

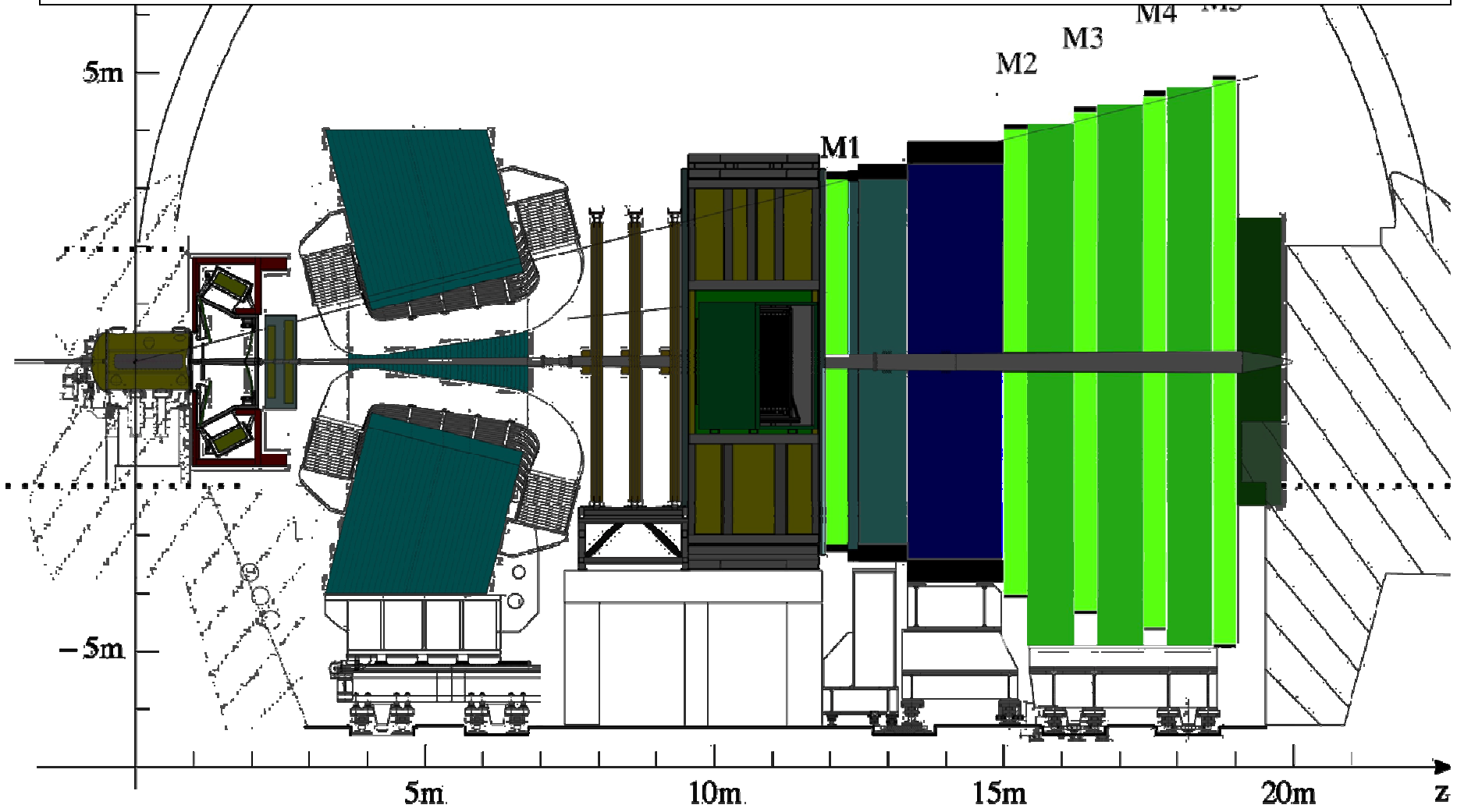
- particle identification; electron, photon, hadron
- trigger (at 40MHz)

(see Miriam Calvo Gomez' talk at this conference)



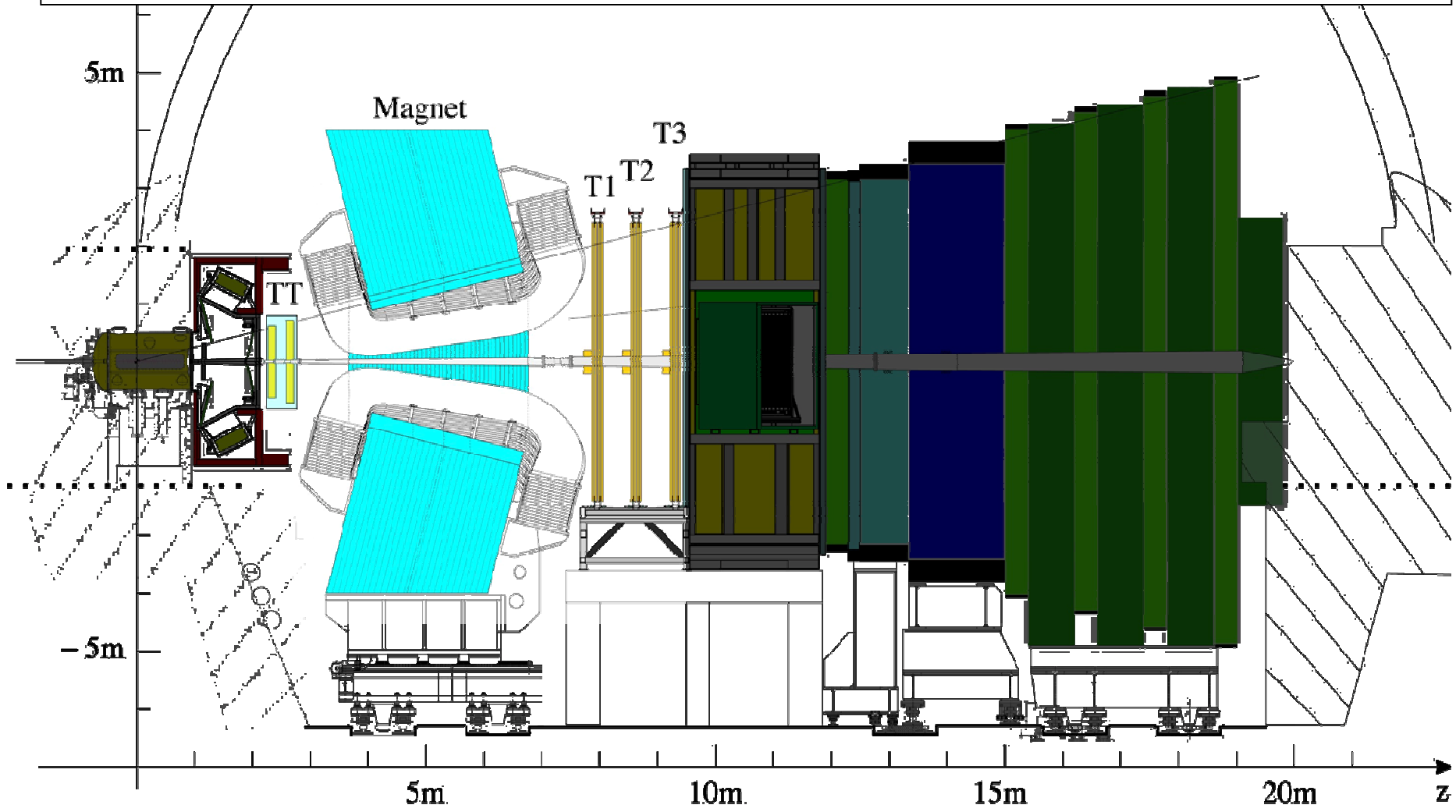
LHCb Detector Slide Show (4)

- muon tracking
- trigger (at 40MHz)

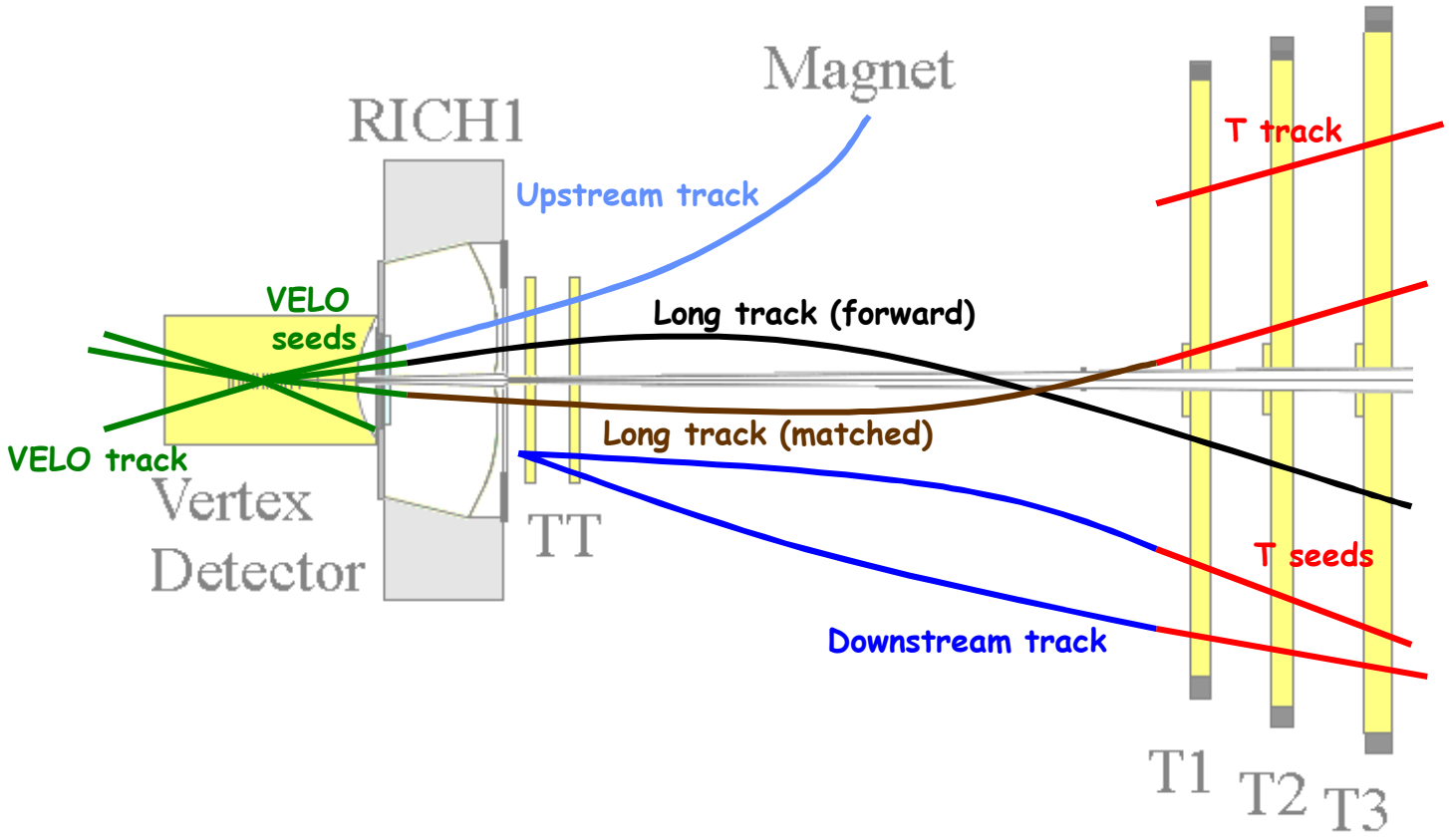


LHCb Detector Slide Show (5)

- charged particle momentum determination
- TT before magnet, Inner and Outer Tracker after magnet



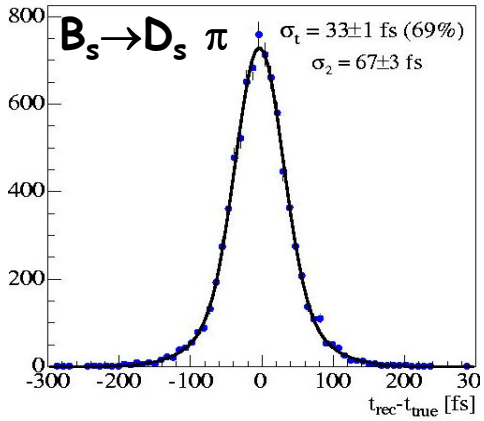
Tracking at LHCb



Long tracks	⇒	highest quality for physics (good IP & p resolution)
Downstream tracks	⇒	needed for efficient K_S finding (good p resolution)
Upstream tracks	⇒	lower p, worse p resolution, but useful for RICH1 pattern recognition
T tracks	⇒	useful for RICH2 pattern recognition
VELO tracks	⇒	useful for primary vertex reconstruction (good IP resolution)

Tracking Performance Goals

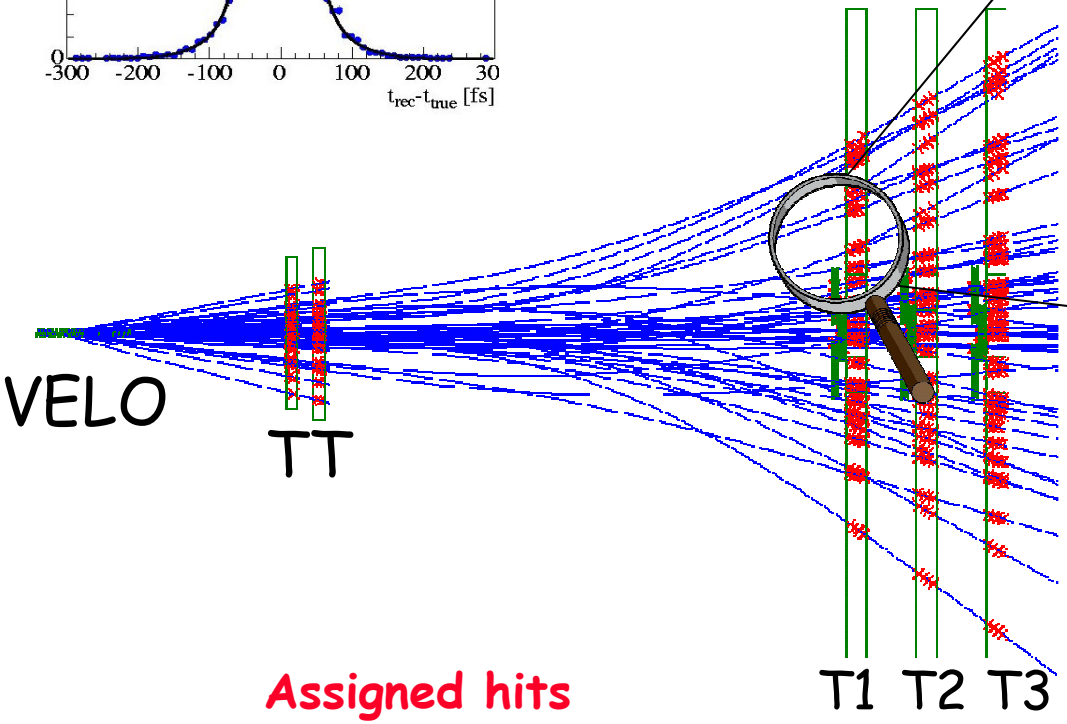
Proper-time resolution



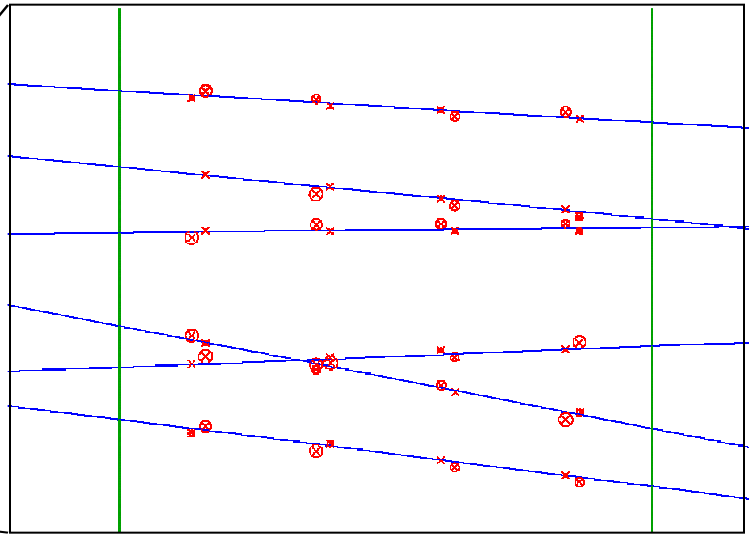
Mass resolution (MeV)

$B_s \to \mu\mu$	18
$B_s \to D_s \pi$	14
$B_s \to J/\psi \phi$	16

($\Delta p/p$ < 0.5%)



Outer tracker station

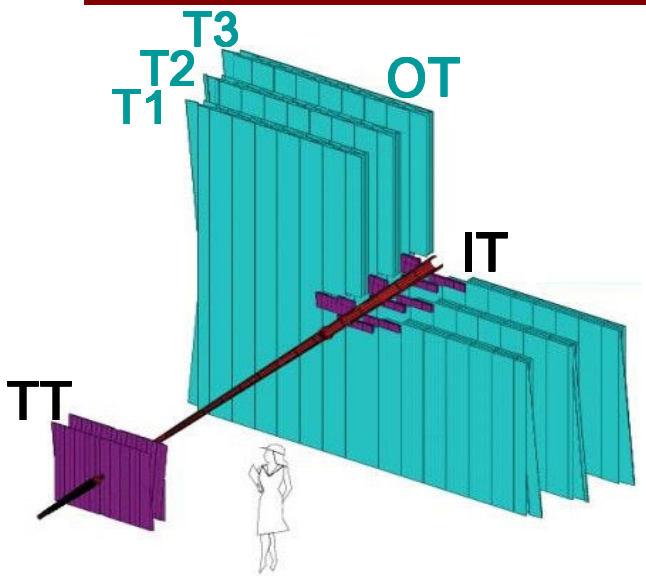


Long tracks:

- ~38 measurements per track
- Efficiency >95% (p>12 Gev)
- Ghost rate <7% (p>12 GeV)
- Robust. Track multiplicity ×2:
  - efficiency 91%
  - ghost rate 14%

Tracking System

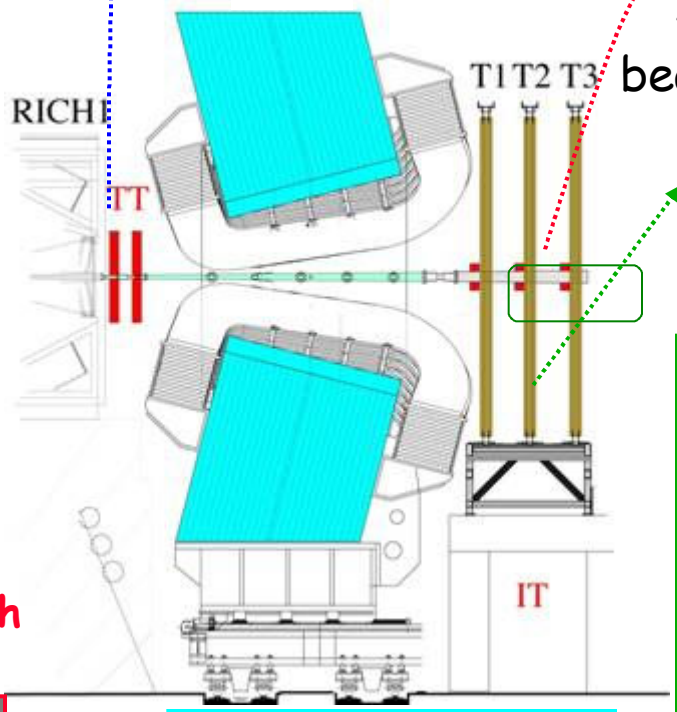
TT + 3 stations (T1,T2,T3), each with 4 detection planes (0^o,$+5^o$,-5^o,0^o)



Trigger Tracker
~1.4×1.2 m² (144k ch)

Inner Tracker
~0.5 m² around beam pipe (130k ch)

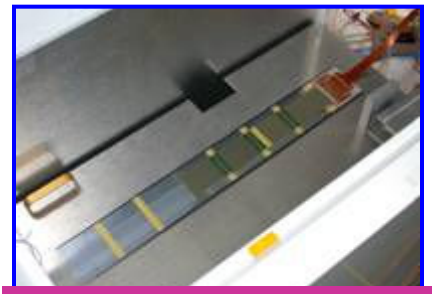
Outer Tracker
Straw Tubes
(56 k ch)

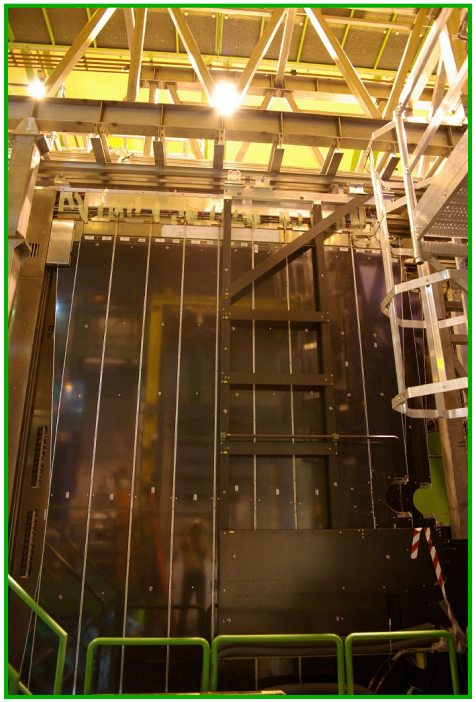


Similar sensors for TT & IT:
Si μ-strip with pitch ~ 200 μm

TT: 128 Modules (7 Si sensors)

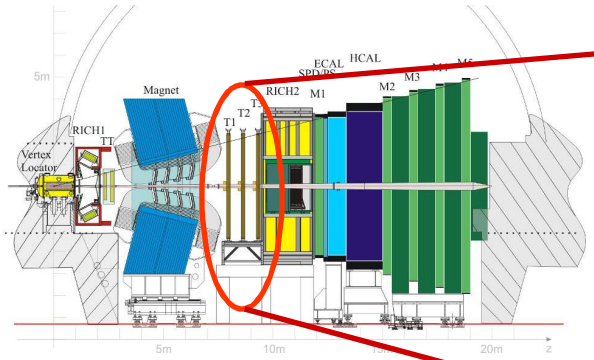
IT: ladders with 1 or 2 sensors

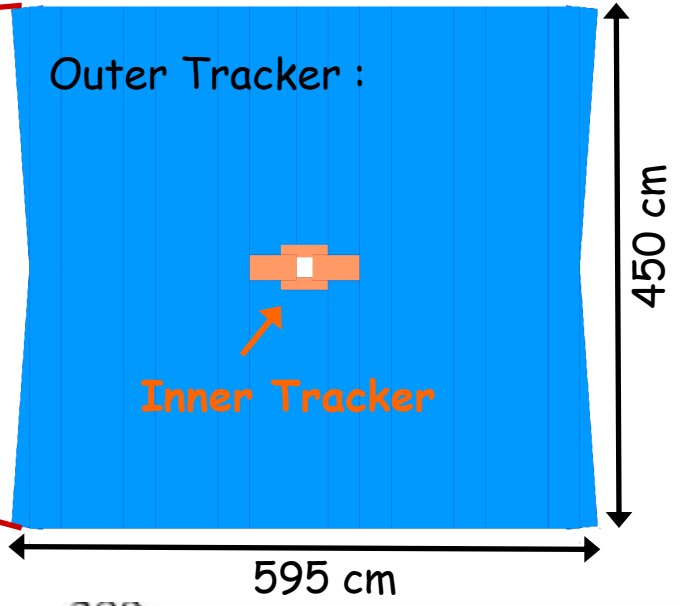




(see J. van Tilburg's poster at this conference)

IT and OT





IT occupancy:

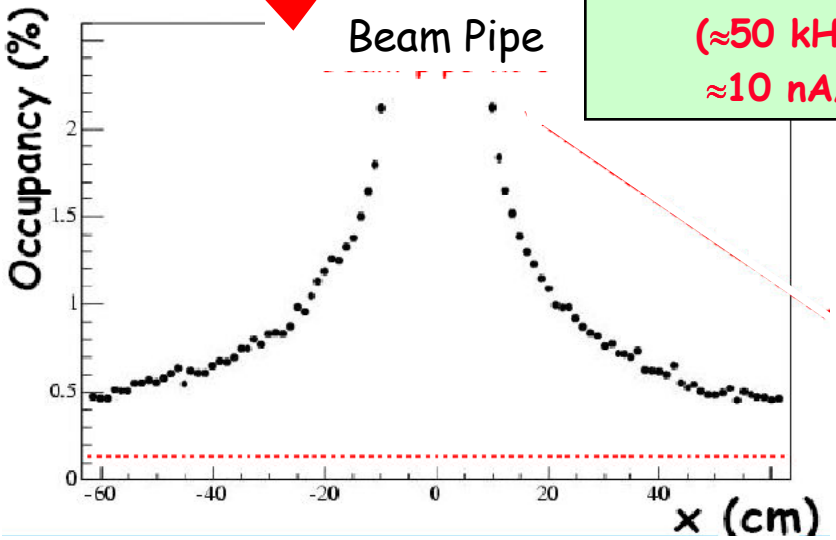
Hottest region = 2.3%

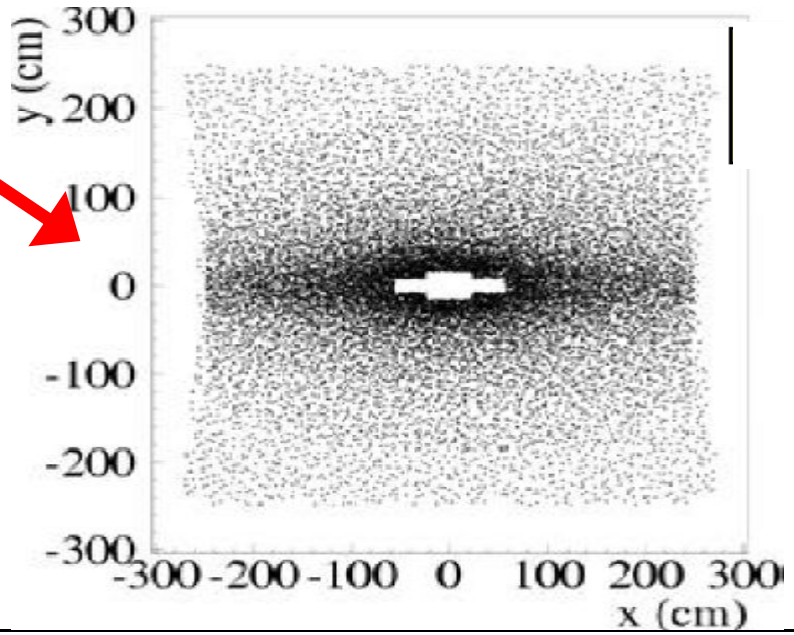
OT occupancy:

Average = 4.5%

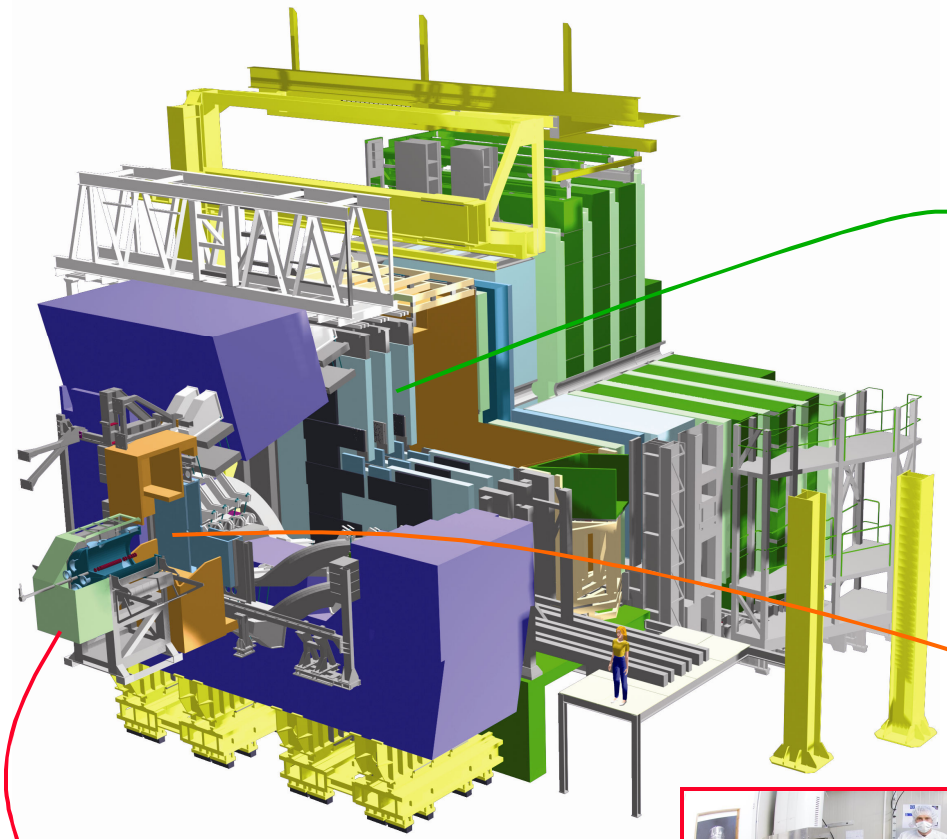
Hottest region = 9%

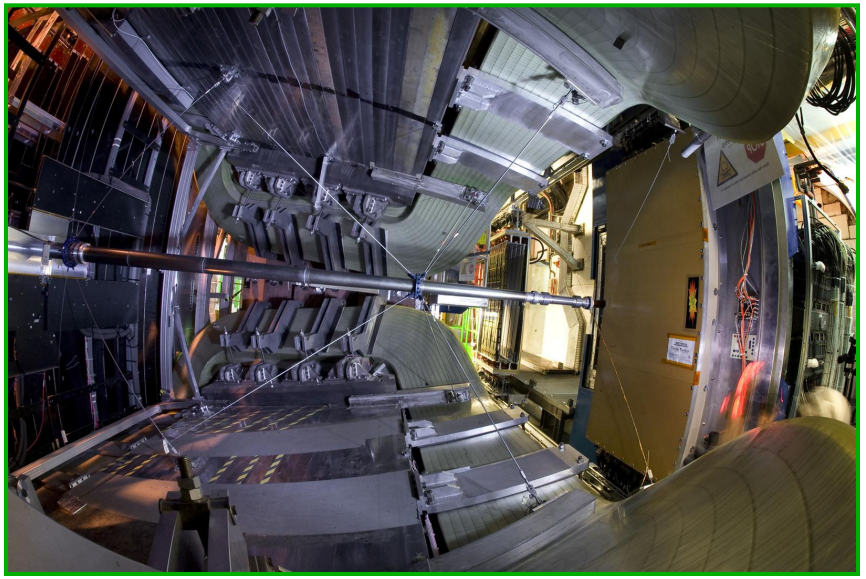
(≈50 kHz/cm ≈10 nA/cm)

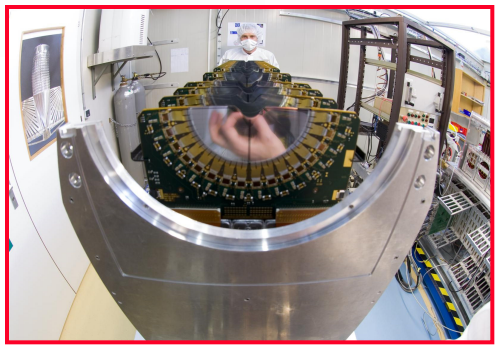


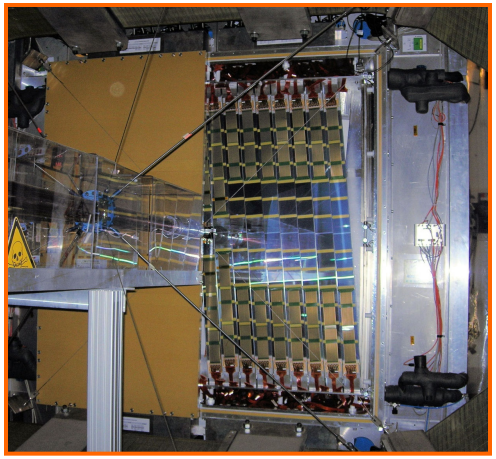


Vertex and Trackers





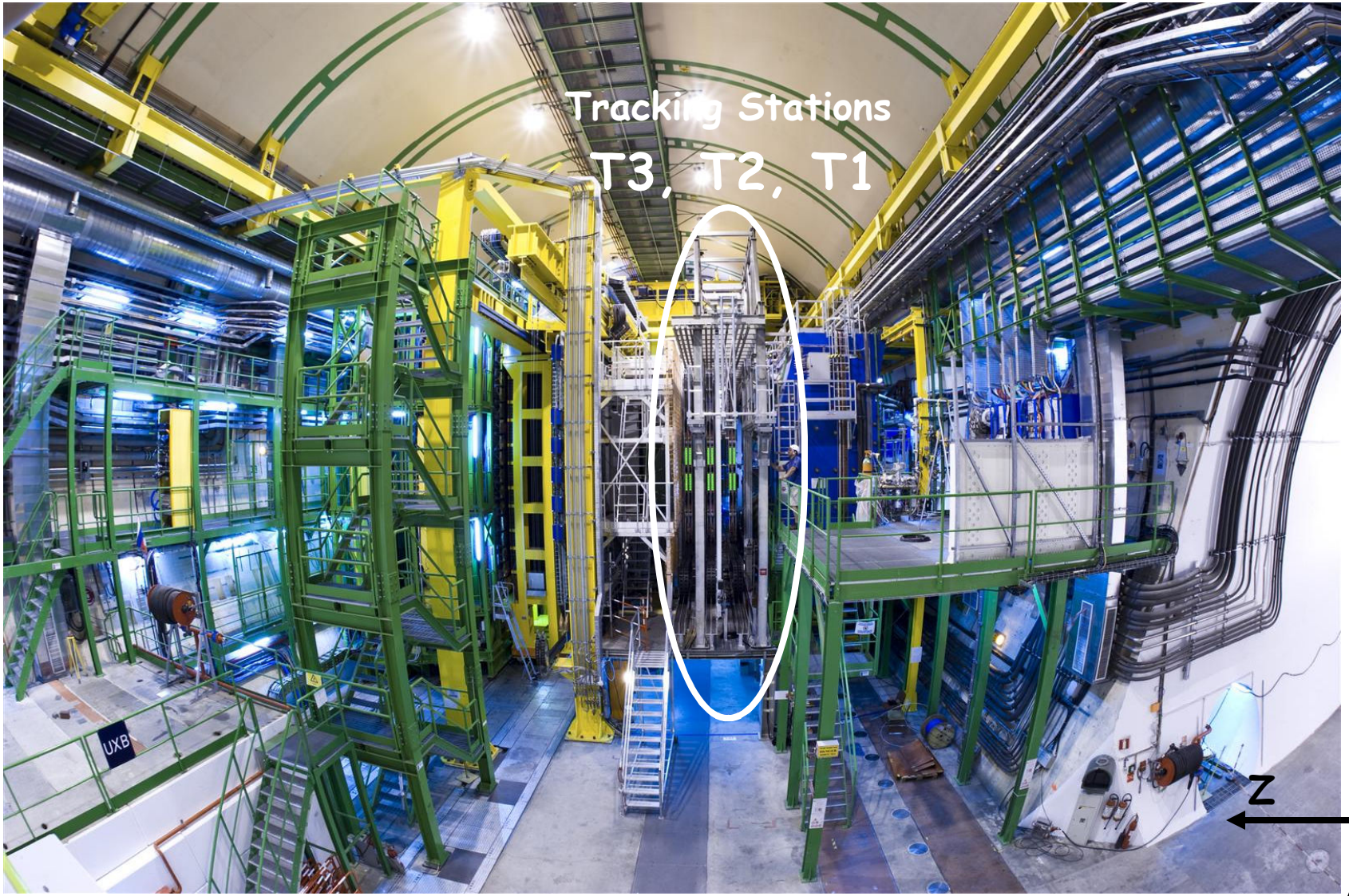




(see C. Parkes' talk at this conference)

(see J. van Tilburg's poster at this conference)

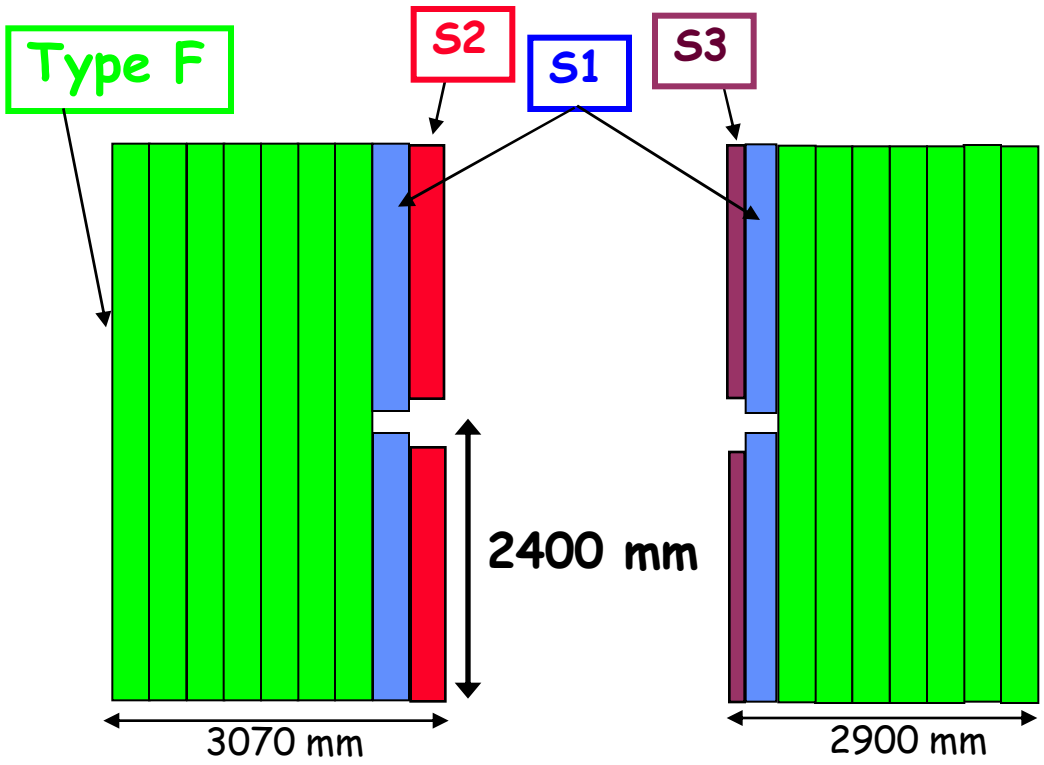
LHCb



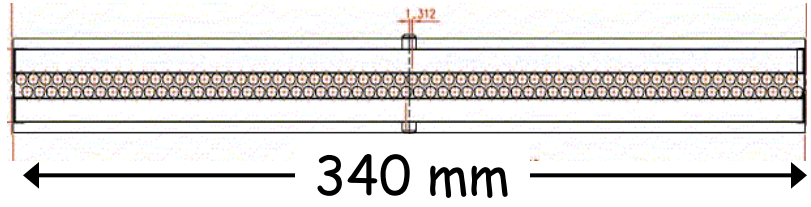
OT Modular Design

Type	Quantity	Spare	Total
F	168	17	185
S1U	24	6	30
S1L	24	6	30
S2U	12	4	16
S2L	12	4	16
S3U	12	4	16
S3L	12	4	16

- **Cracow**: all straw-support panels
- **Warsaw**: 124 *short* modules (6 types)
- **Heidelberg**: 62 *long* modules
- NIKHEF: 130 *long* modules



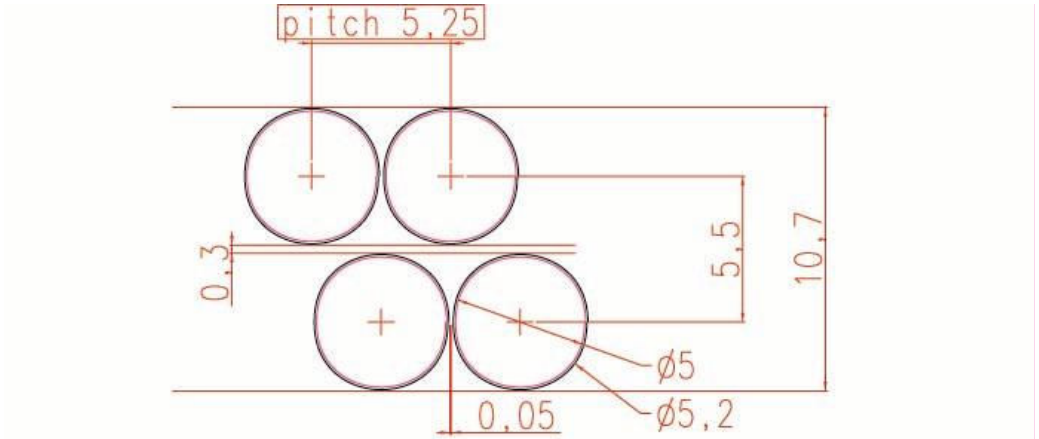
One large module:
- 34 x 490 cm^2
- 4 x 64 = 256 channels

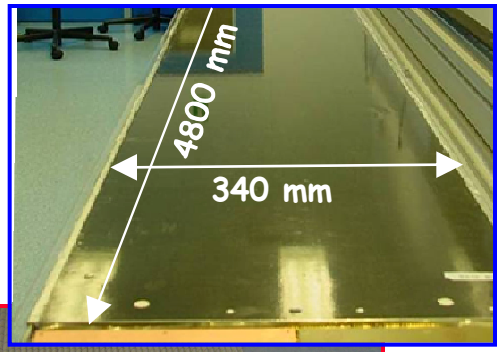


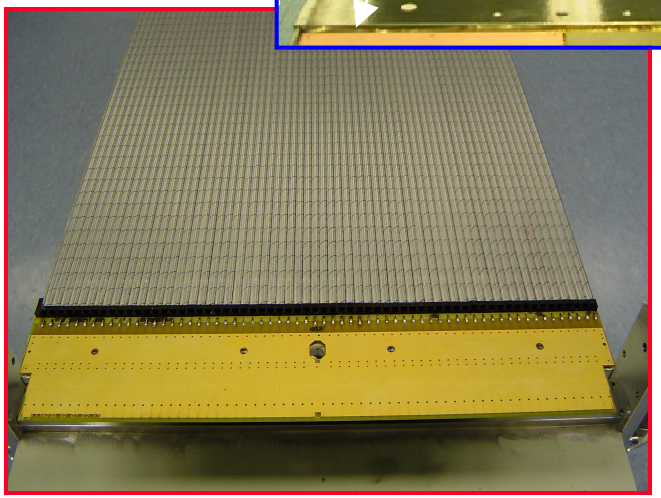
i.e. assembly of
- 56,000 straws
- 56,000 wires
- 200,000 soldered joints
- 620 panels
- 185 F and 124 S Modules

Straw Tubes Modules

Straw Tubes packed in double-layered modules







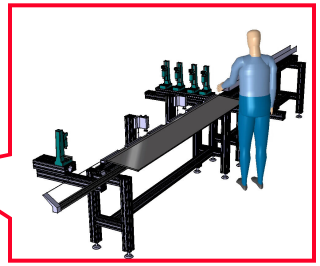
- modules 64-cells wide
- modules only ~0.37% of 1 X_0
  - "light" panels (Rohacell core with carbon fiber skins)
  - "light" straws

Module Production

Prepare straws:

Cut to length, insert wire locators and end-caps, prepare GND contact

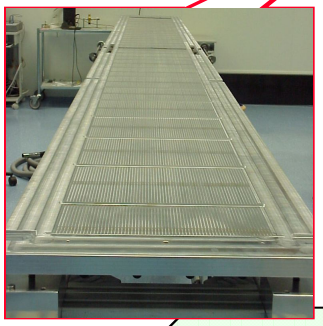
Straw Preparation Tool

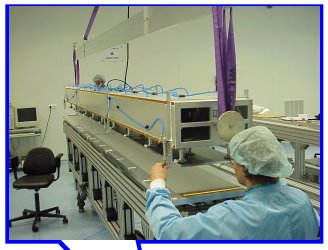


Align Straws:

Position straws in a template jig together with wire-support PCBs

Straw Template Tool

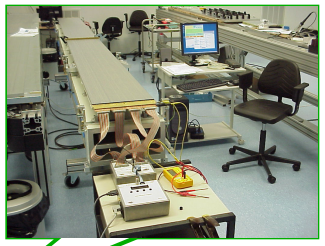




Prepare Panel:

Lay panel flat on

Panel Handling Tool



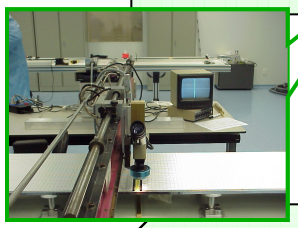
Glue mono-layer:

Join and glue panel/straws/PCBs

(one-night glue curing)

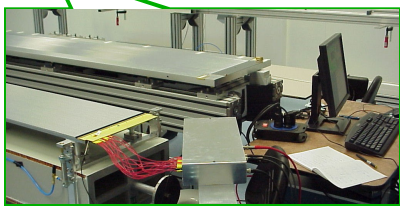
String and solder wires

Measure Wire Position



Measure Wire Tension

Measure Leakage Current



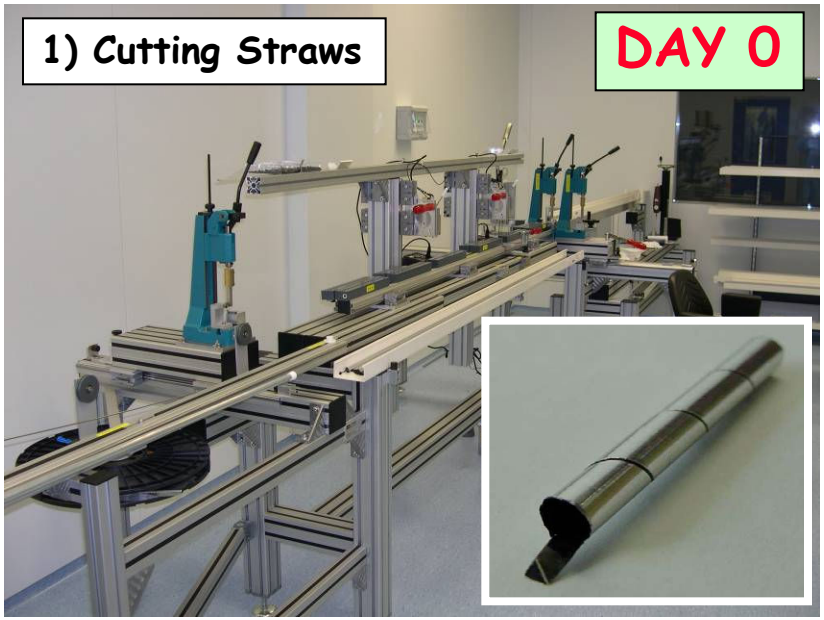
Glue two mono-layers and seal gas box

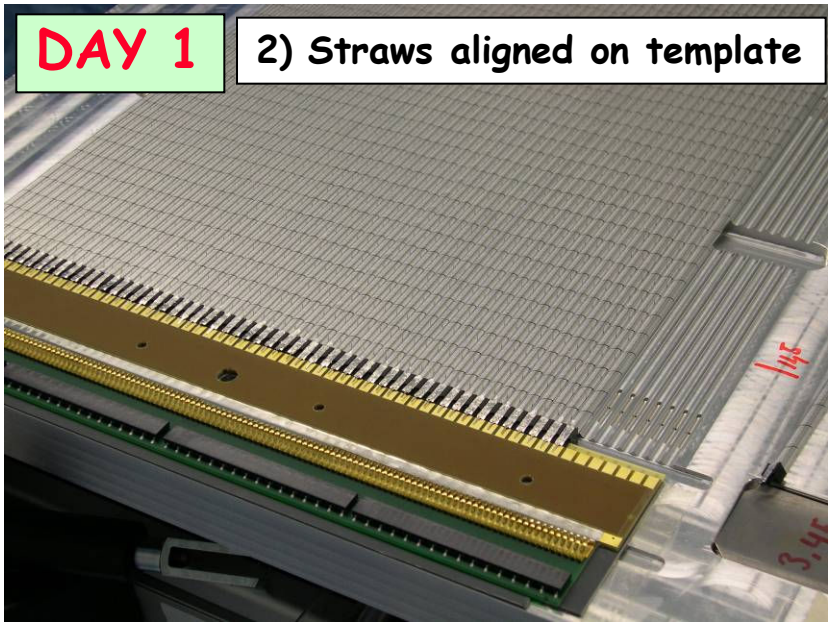
(one-night glue curing)

Scan Modules with ^{90}Sr

Check Gas Tightness

Photo-gallery (day 1)





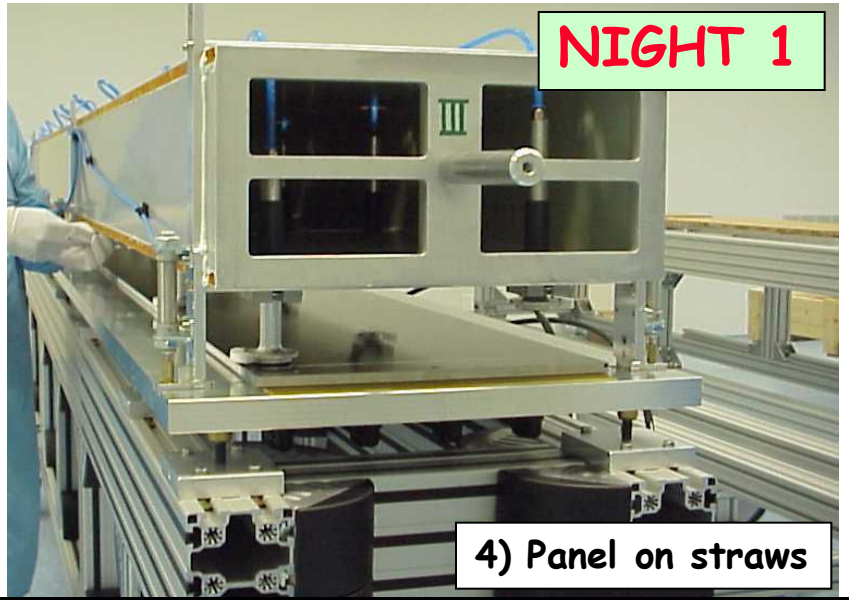
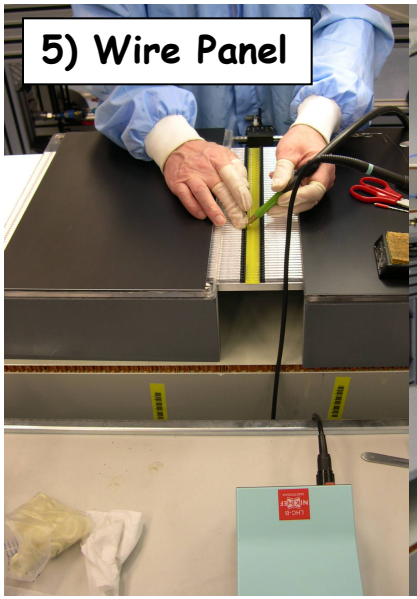
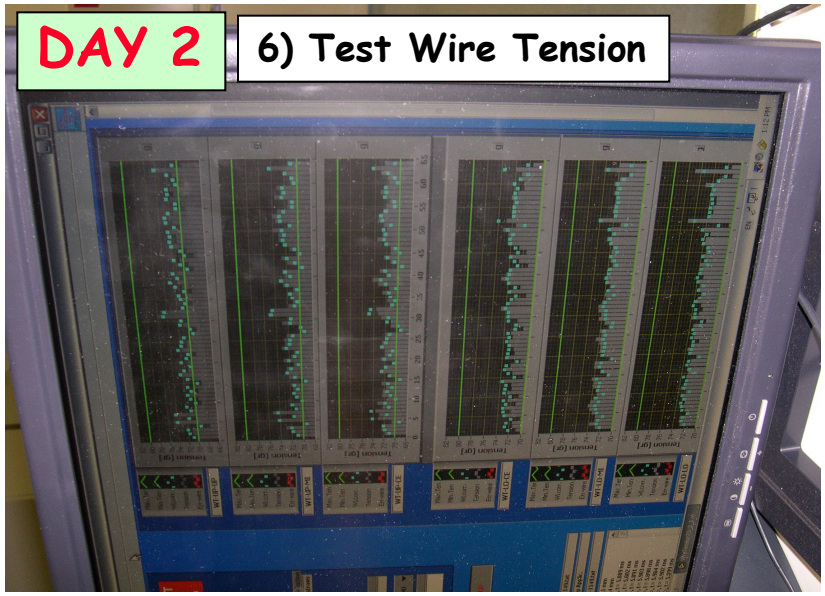


Photo-gallery (day 2)


5) Wire Panel


DAY 2


DAY 2 6) Test Wire Tension


DAY 2

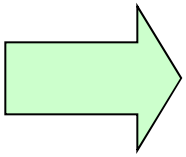
7) Test Wire Dark Current


NIGHT 2

8) Seal Two Panels

Quality Assurance

Detector Module mass construction ~ assembly of:
- 56,000 straws
- 56,000 wires
- 200,000 soldered joints
- 620 panels
- 185 F and 124 S Modules



Quality Assurance during production:
- Wire tension
- Dark current
- Wire pitch

Quality Assurance after production:
- Gas Tightness, Dark current
- detector response to ^{90}Sr β-source

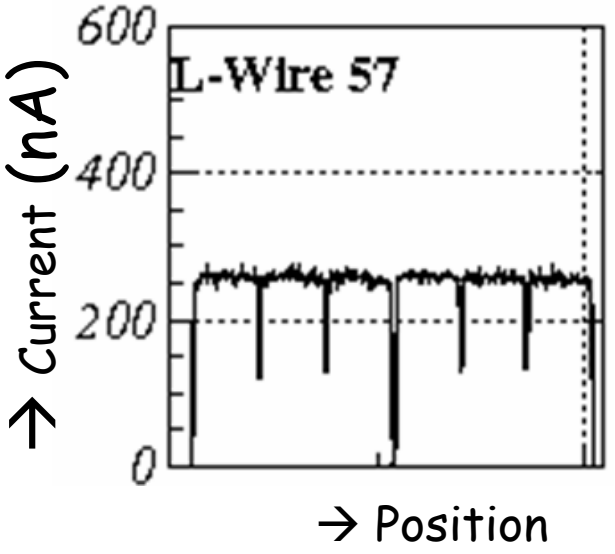
  Full scan (every cm^2) of all OT modules

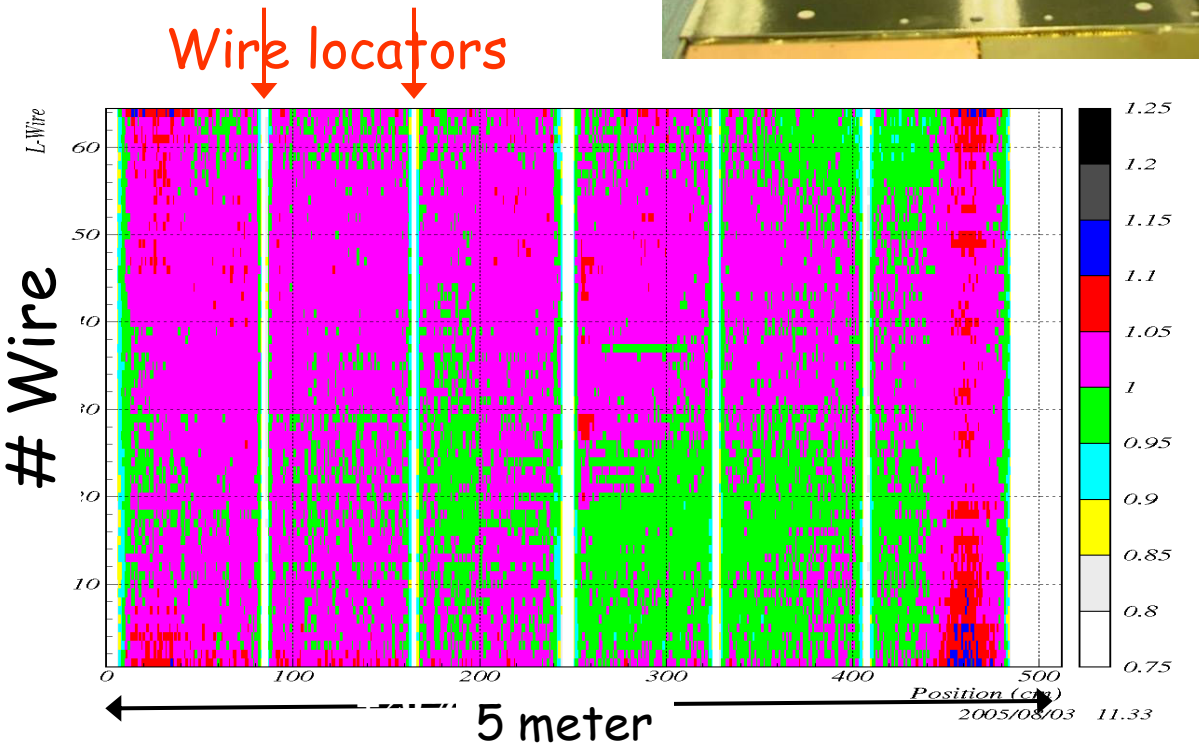
All quality plots for each module can be found here:
www.nikhef.nl/pub/experiments/bfys/lhcb/outerTracker/QualityPlots/

^{90}Sr scans

Check detector response:

- Current from ^{90}Sr β-source
- Pulse height from monochromatic ^{55}Fe γ-source
- Full scan of the entire module
  - Every cm^2 of the OT is checked



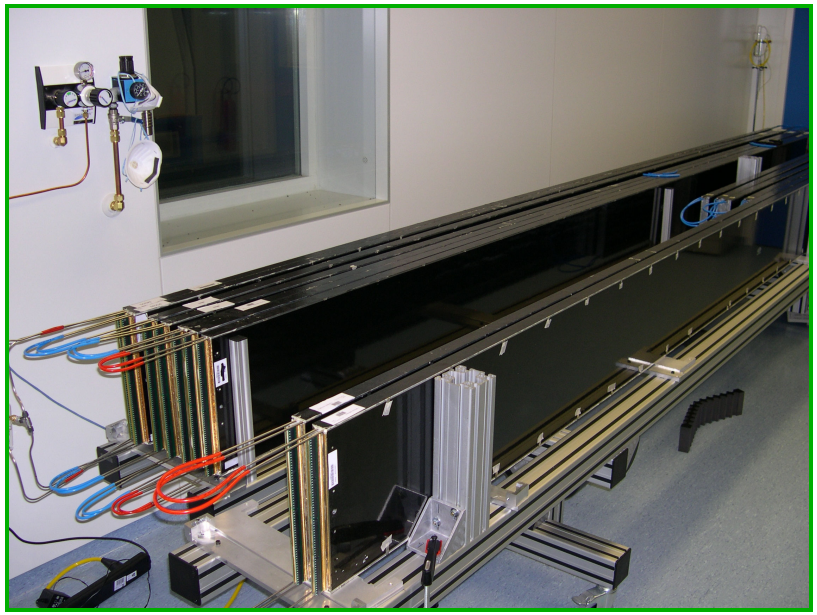


Production Summary

Module Classification (1st choice, 2nd choice, etc.) based on:

- ✓ **Dead channels:** in general disconnected shorts (0.6‰)
- ✓ **"Noisy" Channels:** high dark current (0.7‰), often "cured" after HV training)

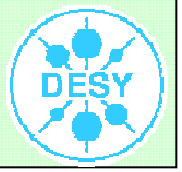
- *70% of bad channels in 10% of the modules (typically the first ones produced)*
- *Remaining modules: <1% bad channels*



All modules produced, shipped to CERN, installed in the LHCb cavern on their mechanical support, and re-tested

Test Beam

- Final detector modules
- Final prototype electronics
- 6 GeV electrons at DESY

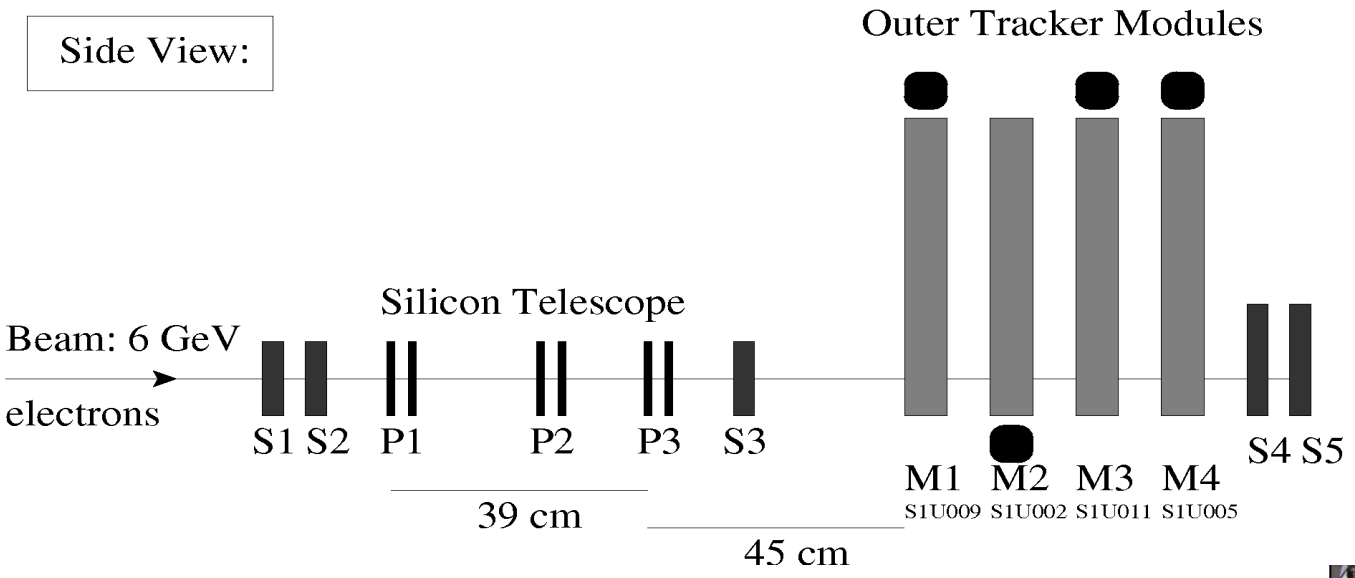


- ✓ Efficiency
- ✓ Resolution
- ✓ Noise
- ✓ Cross talk

vs

- HV
- Amplifier threshold
- Position along straw

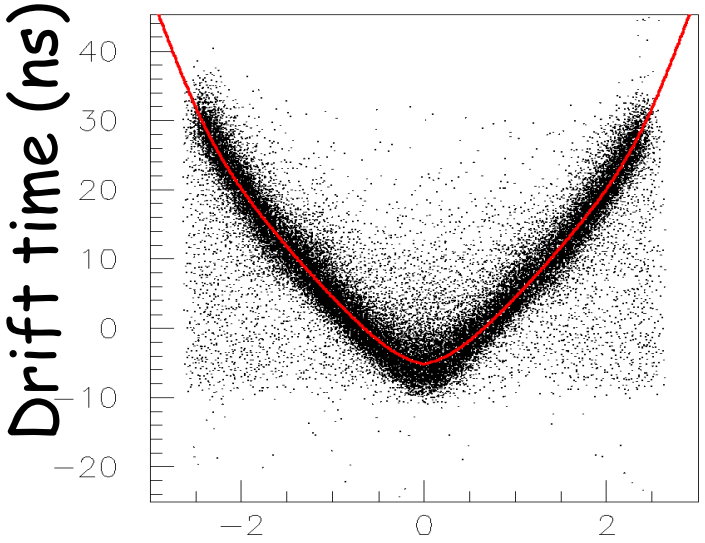
Side View:

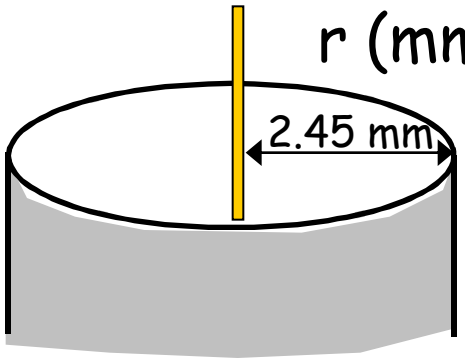


See LHCb Note: LHCb-2005-076

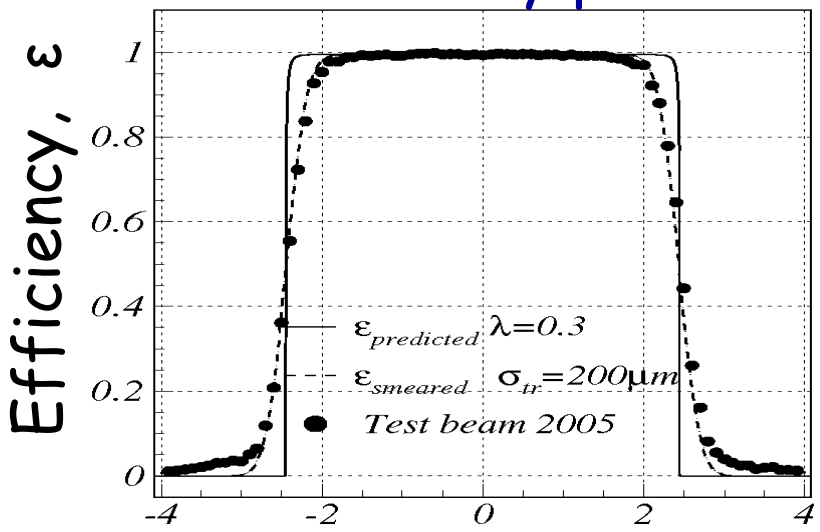
Test Beam Results

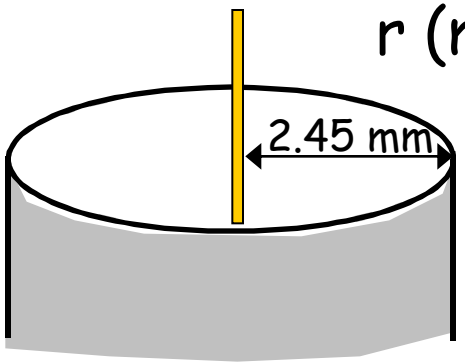
rt-relation:





efficiency profile:

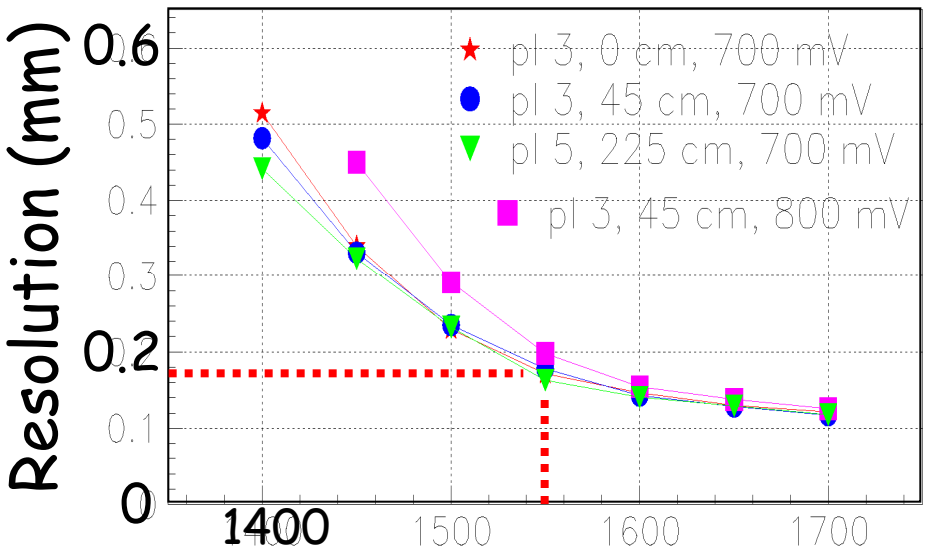


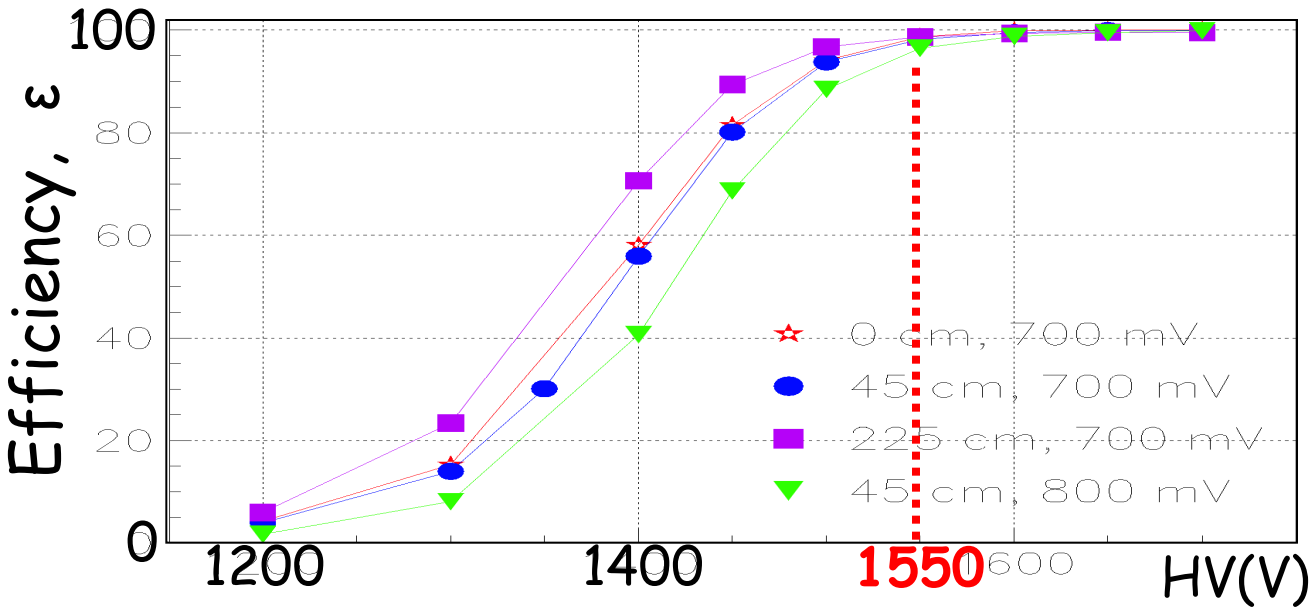


Next Page ⇒ Resolution and efficiency for different HV and amplifier threshold

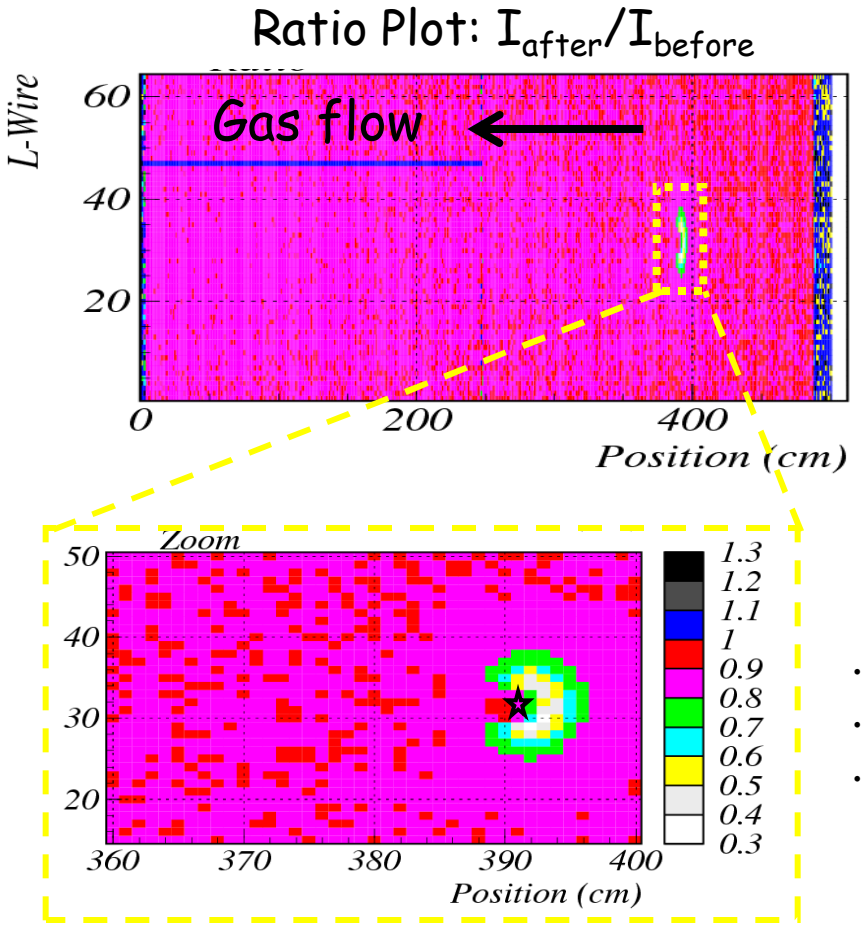
Test Beam Results (cont'd)

- Good efficiency and resolution for HV > 1520 V
  - ✓ ε ≈ 98%
  - ✓ σ ≈ 200 μm
- Corresponds to Gain > 50,000

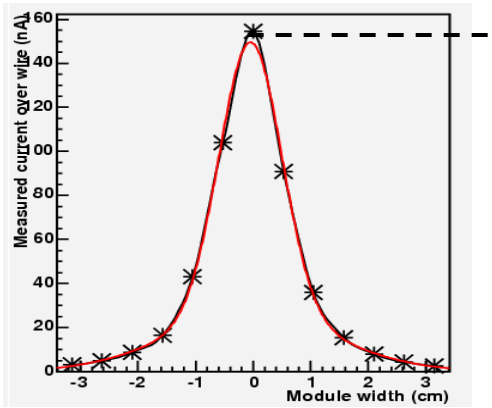




Ageing Surprise!



Irradiate with 2 mCi ^{90}Sr source



The ageing of the LHCb OT exhibits **unique features**:

- The ageing rate is large
- No ageing below the source
- No ageing downstream of the radioactive source

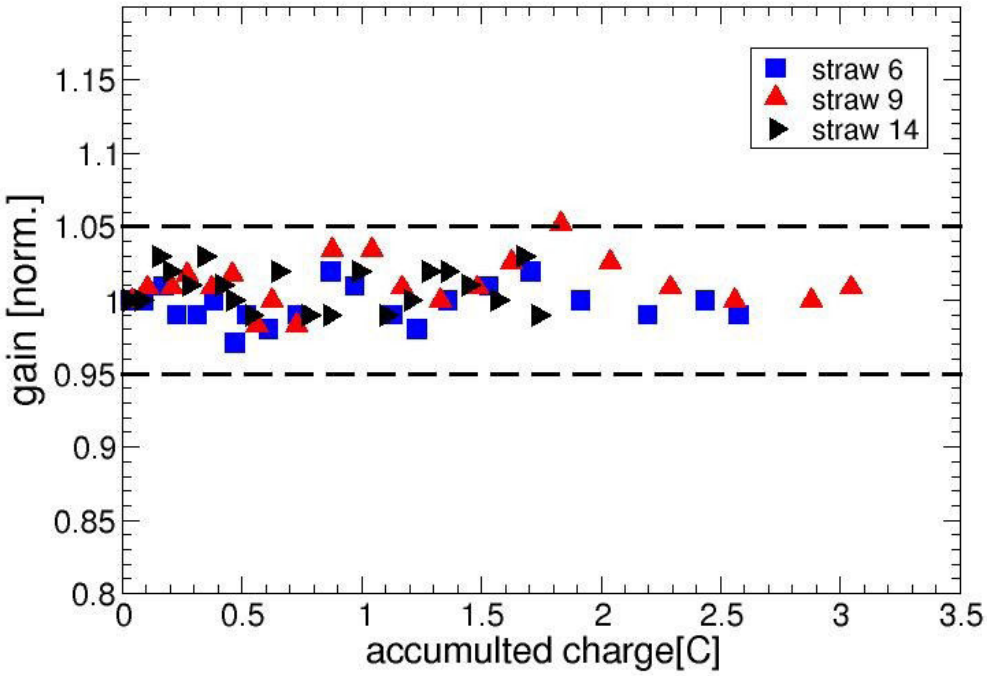
A real surprise – this had not been seen in the ageing tests performed with test modules in the R&D phase

Ageing R&D

Accumulated 3 C/cm (>10y in LHCb hottest spot) in 120 days ⇒ **No effects seen**

Ageing Studies in R&D phase (test modules):

- 12 MeV proton beam
- Hadronic environment (in situ HERA-B)
- 9 keV X-ray tube.



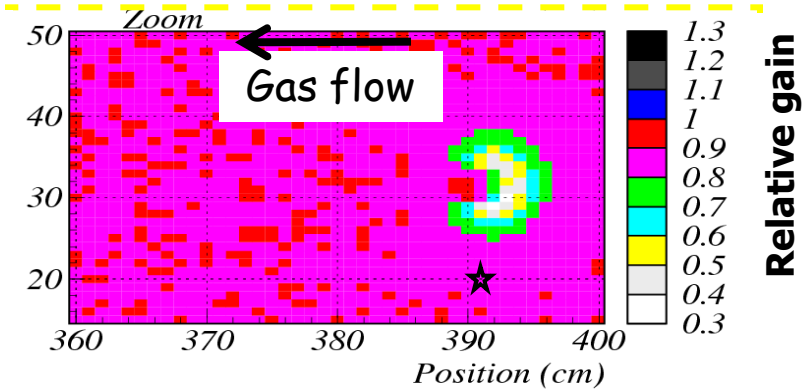
IEEE 2004 NSS-MIC conference **(Oct 2004, Rome)** by Sebastian Bachmann

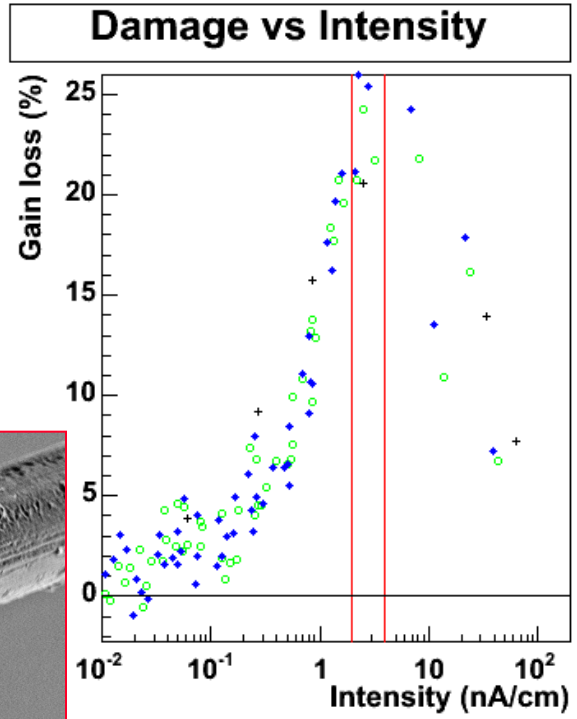
- Session N39: Radiation Damage Effects II - Aging of Gaseous Detectors
- Title: *Ageing Studies for the Straw Tube Detectors for the LHCb Outer Tracking System*

Ageing References

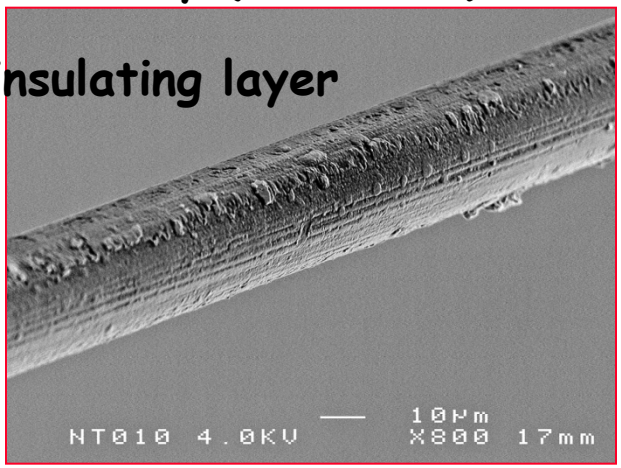
Needs a dedicated talk, but see *Ageing in the LHCb outer tracker: Phenomenon, culprit and the effect of oxygen*, Nuclear Instruments and Methods in Physics Research Section A, Available online 10 November 2009, ISSN 0168-9002, DOI: 10.1016/j.nima.2009.10.049 (http://dx.doi.org/10.1016/j.nima.2009.10.049)

Presented by M. Blom at the 11th Pisa meeting for advanced detectors, Elba, Italy 25-29 May 2009





- Gain loss only at moderate intensity (≈2 nA/cm)
- Upstream of gas flow
- SEM/EDX ⇒ thin (<1 μm) insulating layer
  - C (and indirectly H)

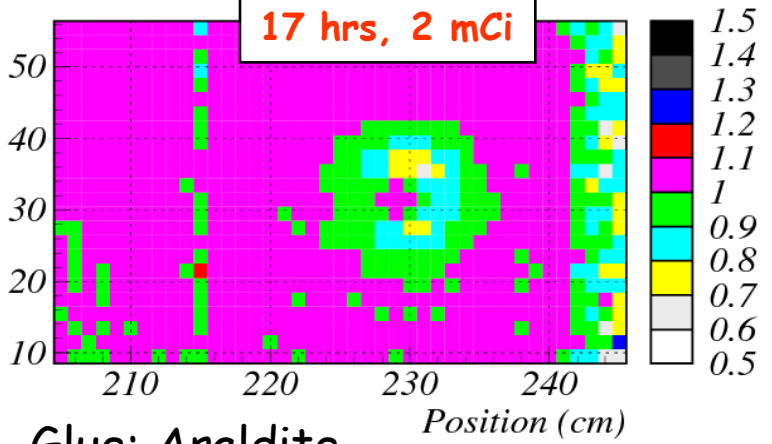


Ageing References (cont'd)

Needs a dedicated talk, but see *Ageing in the LHCb outer tracker: Phenomenon, culprit and the effect of oxygen*, *Nuclear Instruments and Methods in Physics Research Section A, Available online 10 November 2009, ISSN 0168-9002, DOI: 10.1016/j.nima.2009.10.049 (http://dx.doi.org/10.1016/j.nima.2009.10.049)*

Presented by M. Blom at the 11th Pisa meeting for advanced detectors, Elba, Italy 25-29 May 2009

Dedicated Test Vessel



Glue: Araldite
AY 103-1, HY991

Standard modules built with different glue (Trabond 2551) ⇒ NO Ageing!!
(Confirms malicious effect of AY-103-1)

Further Ageing Studies – AY103

During our tests, we came to realize that:

For mass production, did not use AY103, but AY103-1
- in 2003 producer switched from AY103 to AY103-1

*"The idea of the change in material status is not one of improvement in **mechanical properties** etc. …*

	AY 103:HY 991 *(100:40 w/w)*	***AY 103-1:HY 991*** *(100:40 w/w)*
Viscosity 25 °C of basic resin (Brookefield RVT, Spindle 4, 50 RPM)	*AY 103 is 1400 - 1800 mPas*	*AY 103-1 is 1800 - 2400 mPas*
Appearance	*Clear liquid, free of impurities*	*Clear liquid, free of impurities*
Gelation time at 25°C (50g bulk, metal rod)	*300-500 mins*	*200 - 400 mins*
*Lap shear strength at 25*C Cured 30 min at 100°C: (Sand blasted aluminium L165, mean of 5 replicates contact pressure)*	*14.0 MPa minimum mean*	*14.0 MPa minimum mean*

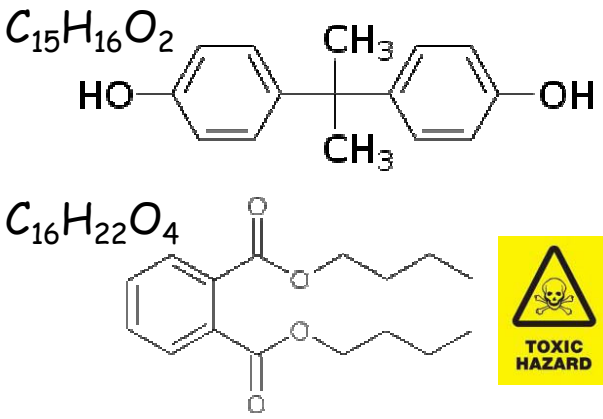
AY103-1 : a Safer Araldite!

*…but one of making it **safer to use** with regard to Health & Safety and complying with European law.*

*… labeled with the Toxic Symbol (skull & crossbones). Araldite AY 103 would fall into this category. Araldite AY 103-1 is the **DBP free version** and should not require such labeling."*

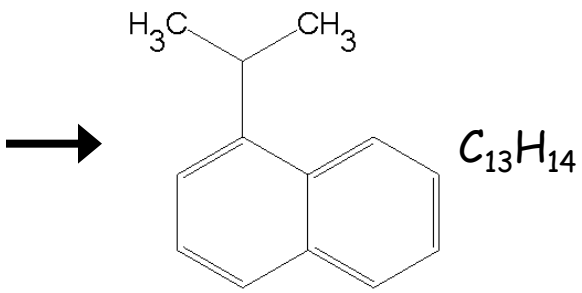
AY103

Chemical Name	CAS-No.	Symbol(s) :	R-phrase(s)	Concentration [%]
reaction product: bisphenol A-(epichlorhydrin); epoxy resin (number average molecular weight < 700)	25068-38-6	Xi, N	R36/38 R43 R51/53	75.00 - 85.00
dibutyl phthalate EC-No.: 201-557-4	84-74-2	T, N	R61 R50 R62	15.00 - 21.00



AY103-1

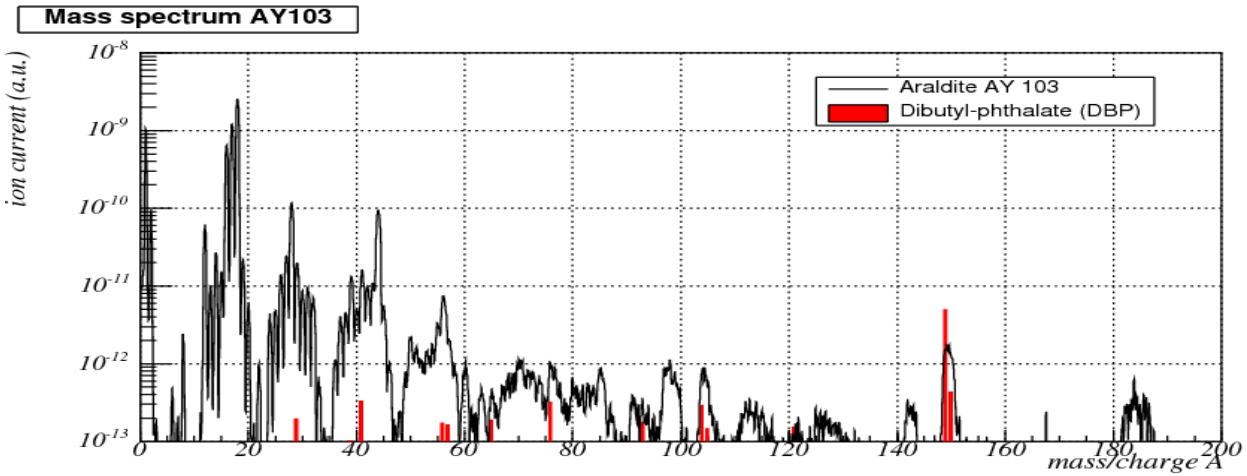
Chemical Name	CAS-No.	Symbol(s) :	R-phrase(s)	Concentration [%]
reaction product: bisphenol A-(epichlorhydrin); epoxy resin (number average molecular weight < 700)	25068-38-6	Xi, N	R36/38 R43 R51/53	75.00 - 85.00
Methyl-ethyl naphthalene (link)	6158-45-8			20

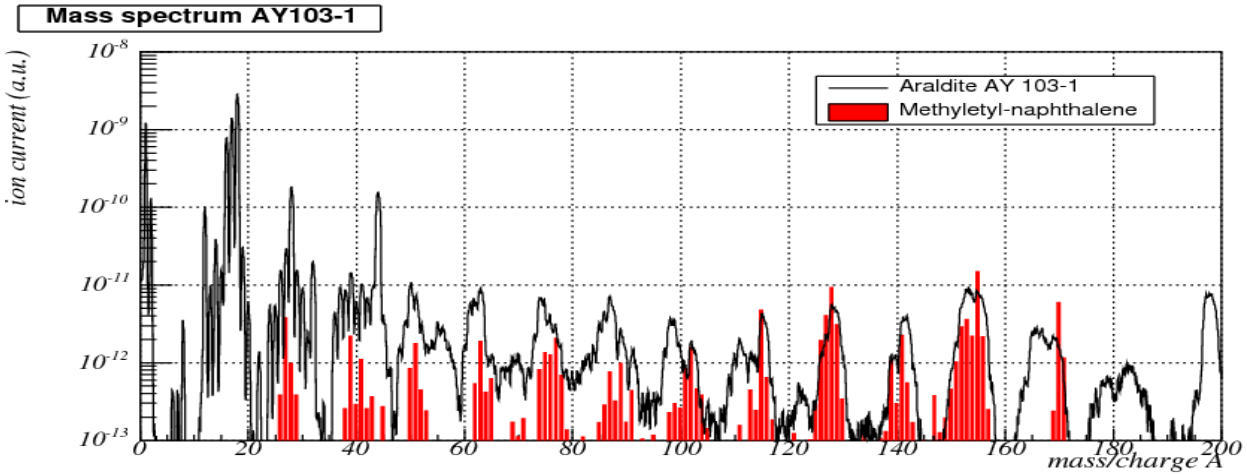


Might this have anything to do with our ageing?

Out-gassing Studies

Glue samples in vacuum in combination with mass spectroscopy





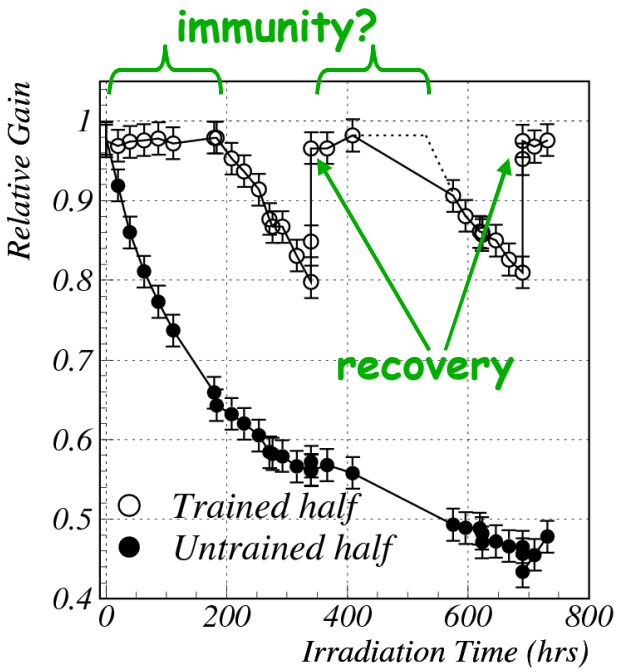
Direct comparisons of AY103, AY103-1 and AY105-1 (100% epoxy, no plastifiers like dibutyl phthalate or methylethyl-naphthalene, thus more viscose) in our test vessel ⇒

- ✓ **AY105-1 no ageing, AY103 significantly less than AY103-1!**

HV Training

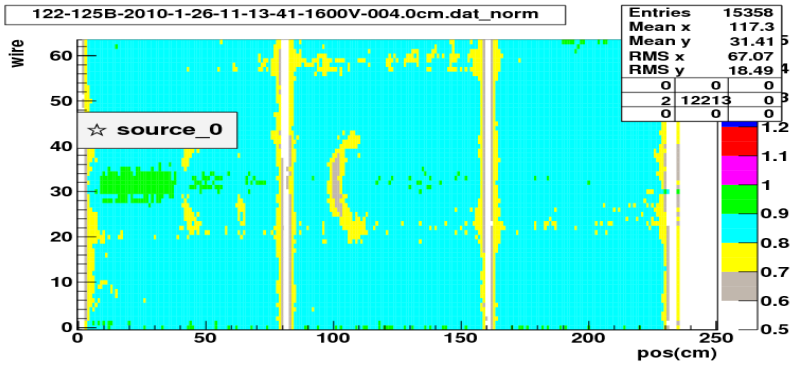
Ageing seems to get less with flushing, addition of ~2% of O_2, lower gas flow, but what to do if…

HV Training!

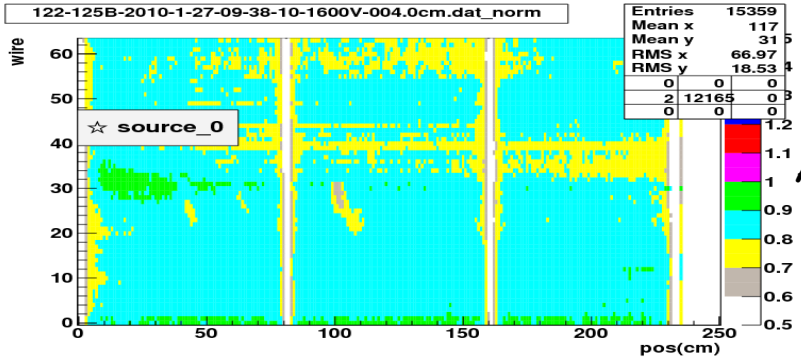


Optical and SEM examination of HV-trained wire sample:

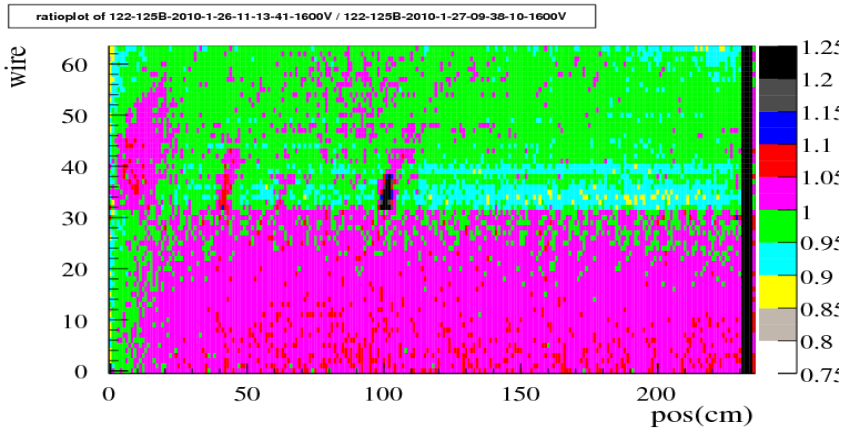
- deposit removed
- Au layer undamaged
- (small C deposit?)



Before training (previous damages clearly visible)

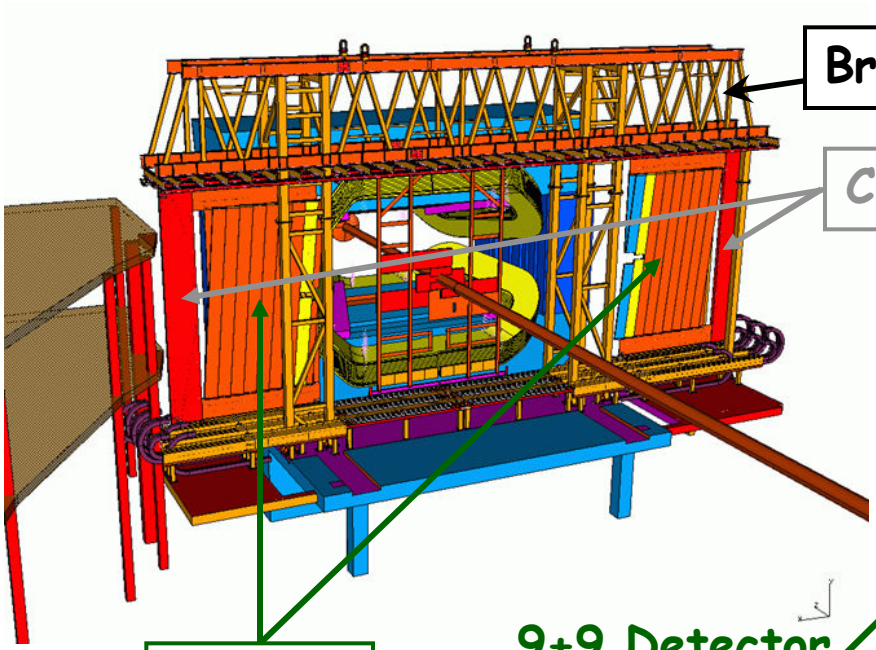


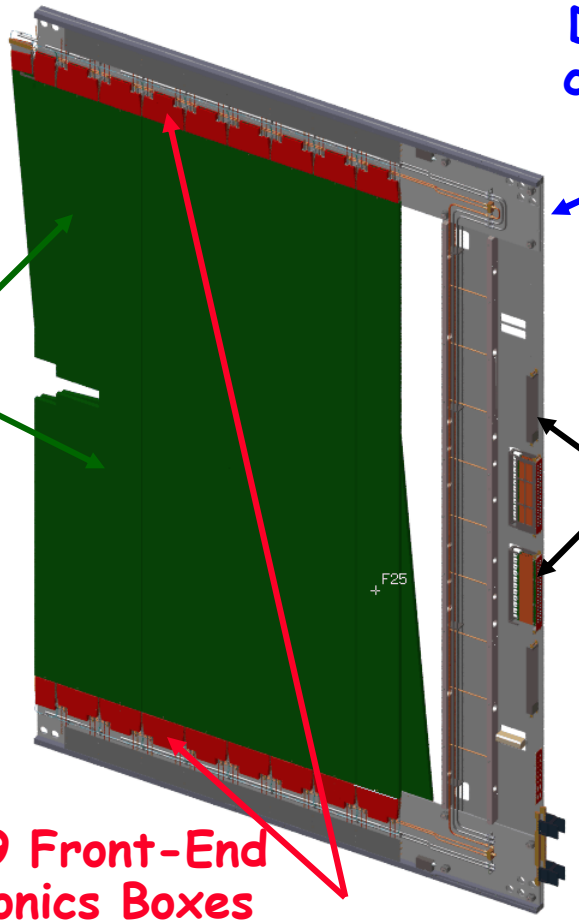
After 15h training at 1900V in situ (only upper half)



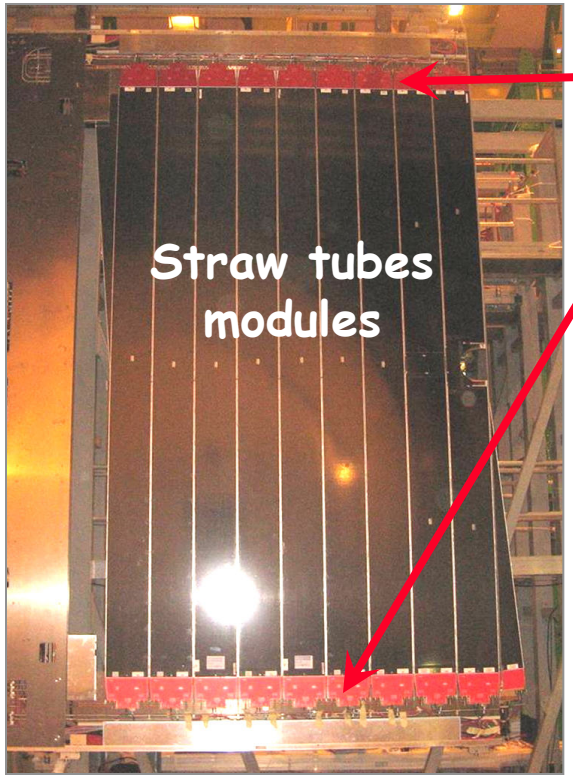
Ratio Plot

OT Installation (1)

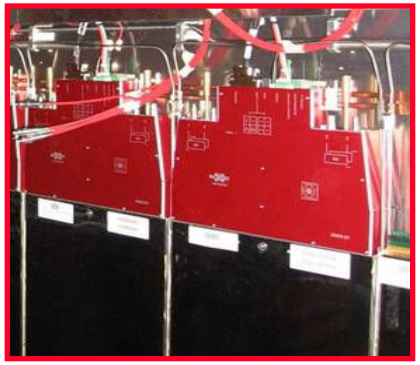


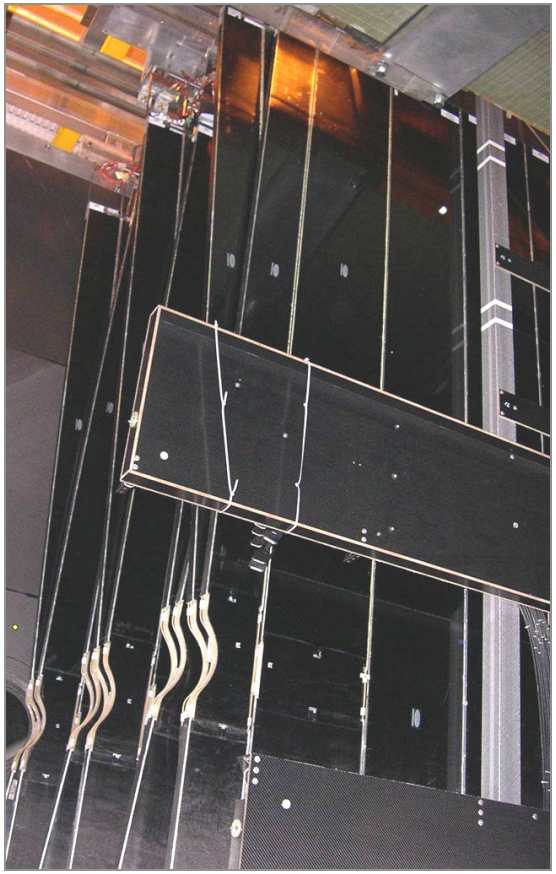


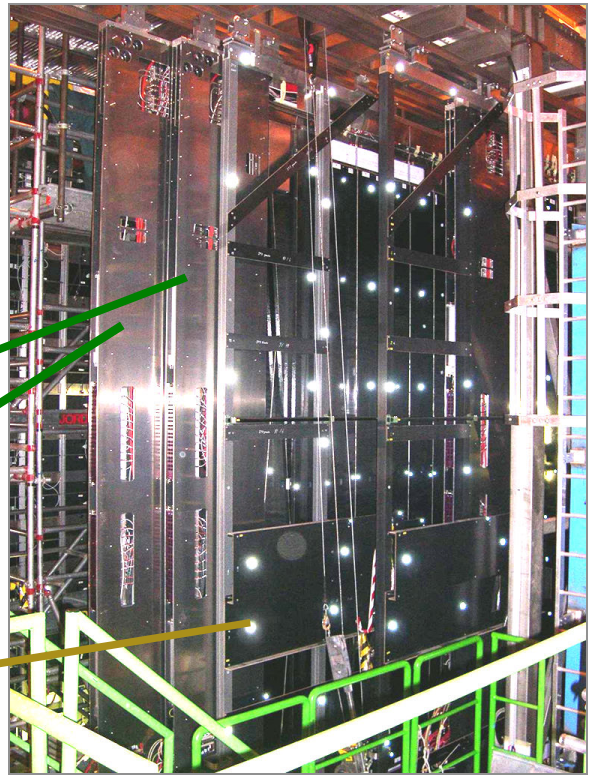
OT Installation (2)



FE Boxes







OT C-frames

survey targets
(photogrammetry)

OT Installation (3)

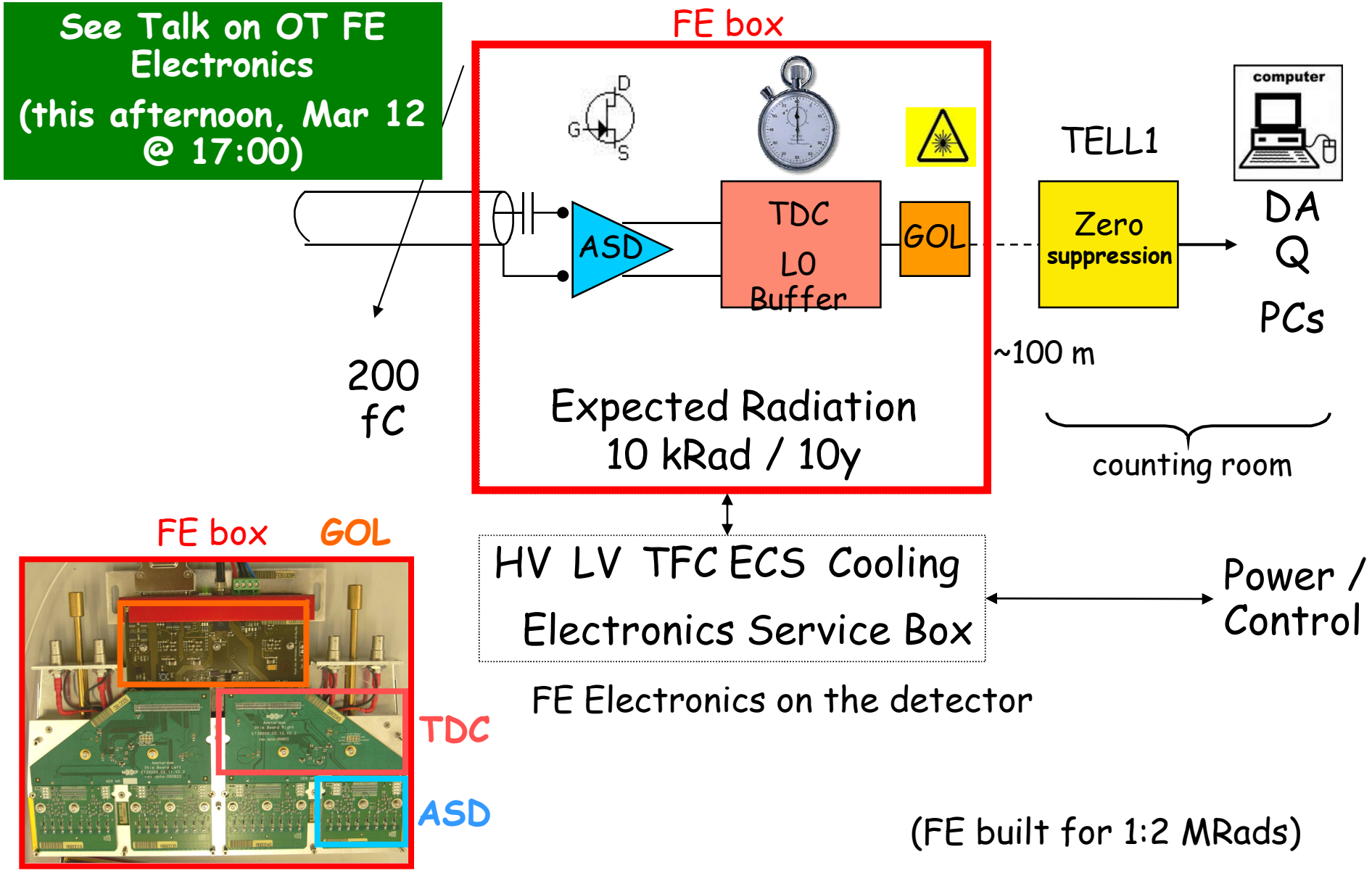
- 2006-2007: Assembly of modules into C-frames and installation of C-frames in detector
- Before assembly of modules, C-frames tested for
  - gas tightness of gas distribution system <1mbar/minute at 10mbar CO_2
  - High Voltage leakage currents <10nA/RMS<1nA
  - Low Voltage connections OK
  - optical fiber attenuation <30dBm
- After assembly of modules into C-frame, modules tested for
  - gas tightness: <1mbar/minute & matching production
  - High Voltage leakage currents minutes 1.8kV-CO_2
- Functionality test with 55Fe source
  - >2700 straws (~$\frac{1}{2}$OT) individually tested
  - 13 dead channels; 11 known at production
- 2008: Installation of FE electronics

oLHCb note *lhcb-2008-033*

OT Installation (4)

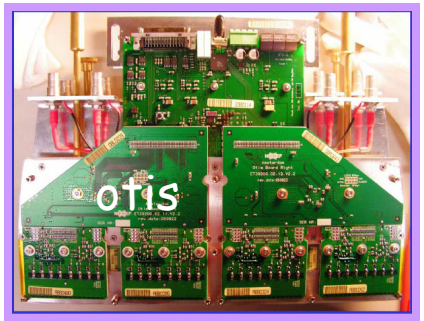
OT Front-End Electronics

See Talk on OT FE Electronics
(this afternoon, Mar 12 @ 17:00)

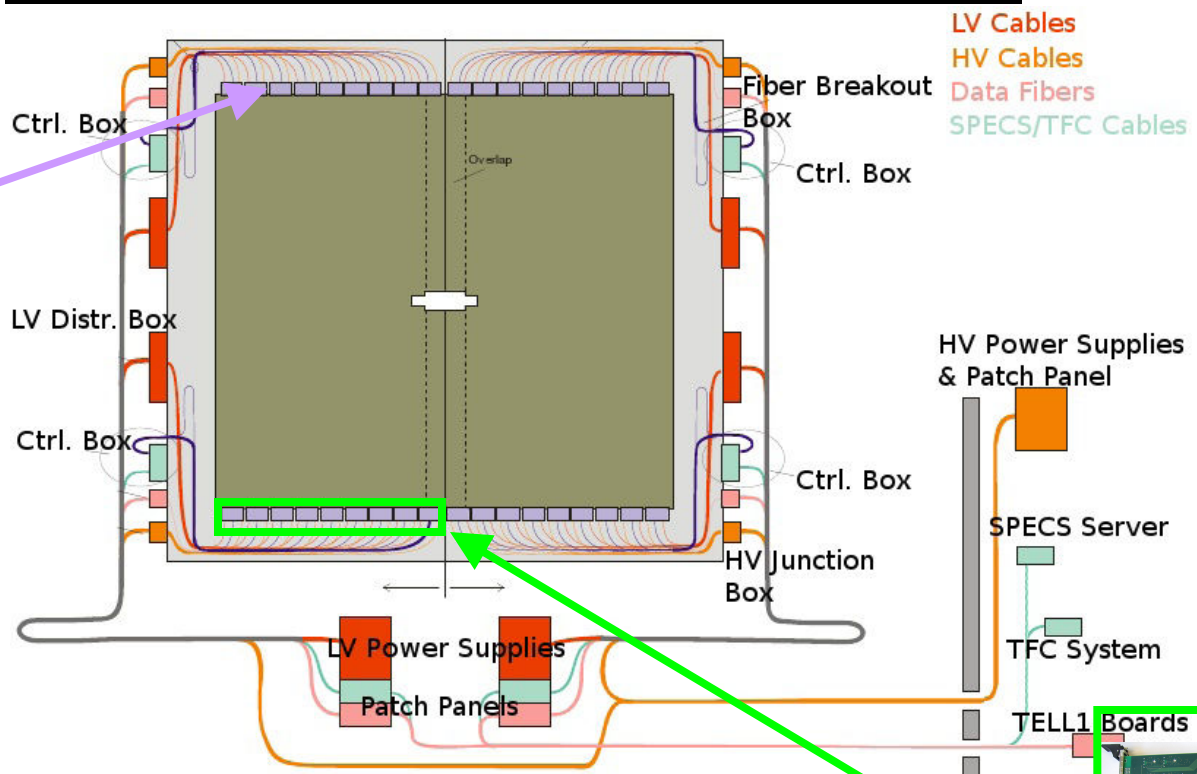


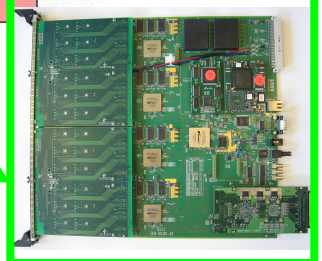
OT Readout

Front view of 2 C-Frames (6+6 in total)



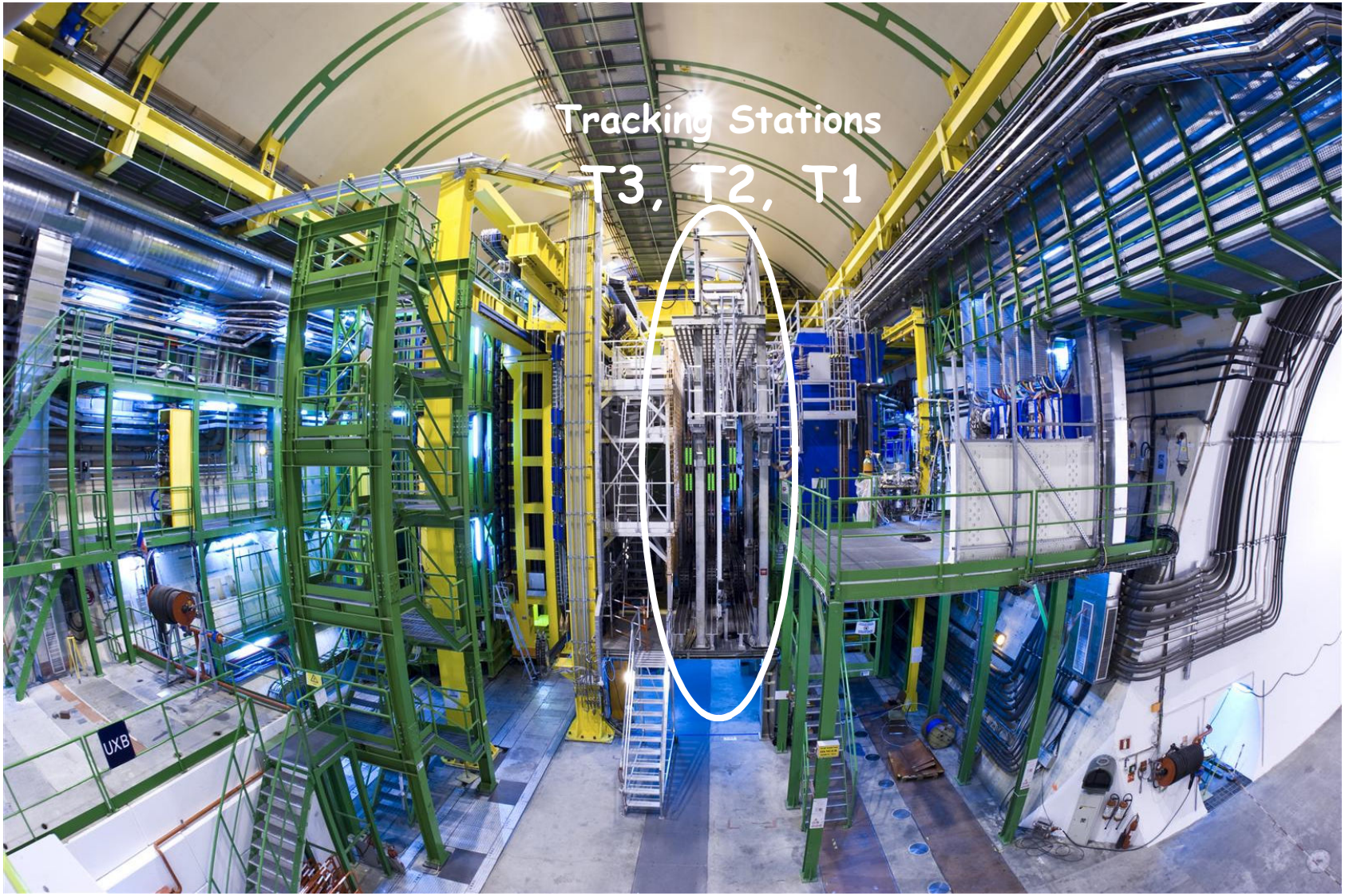
Front-End Board





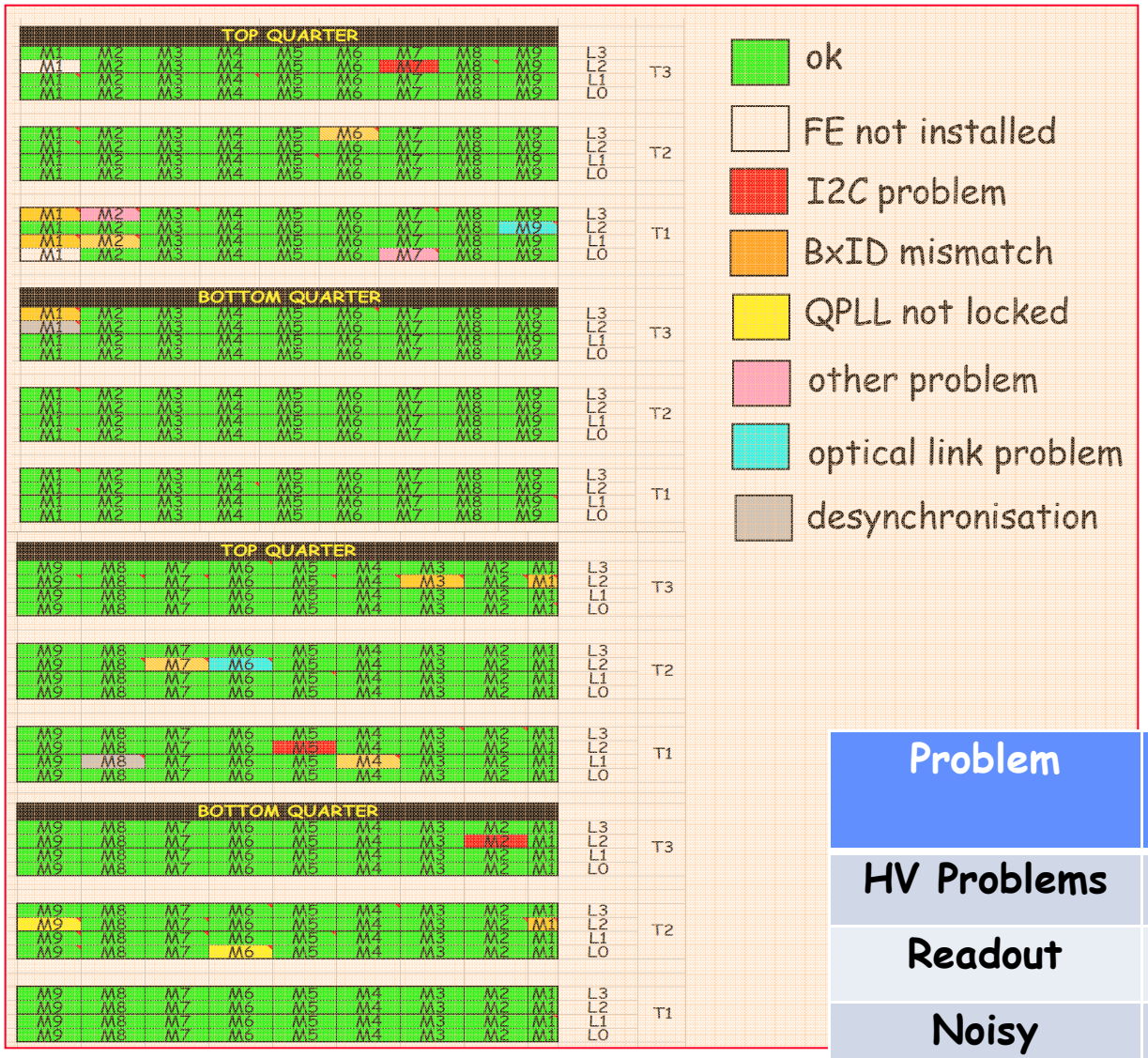
Reads out 9 optical links (1 quadrant)

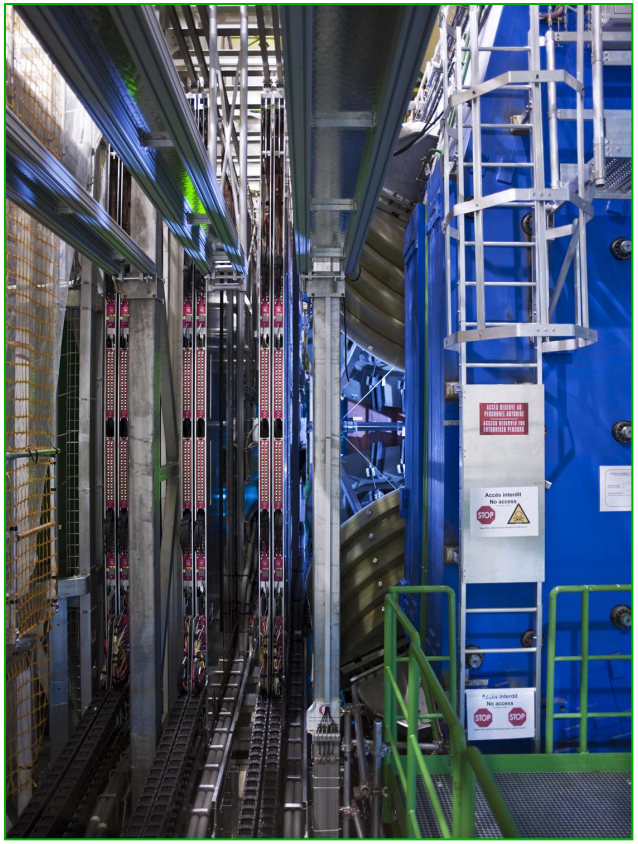
LHCb



Commissioning

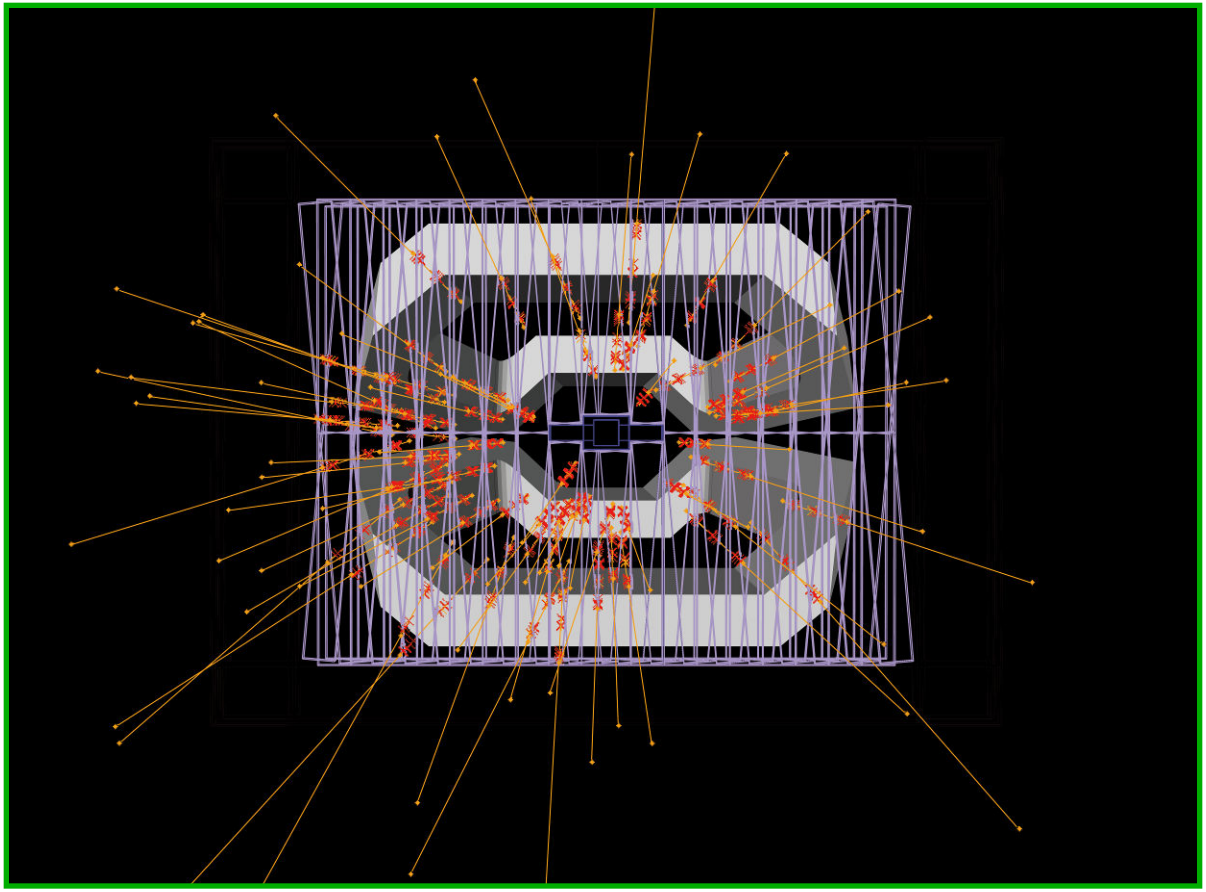
Status before 2009 Data Taking





Problem	2009 Data Taking	After Repair in 2010
HV Problems	1.31 %	0.7 %
Readout	0.6 %	0.0 %
Noisy	0.24%	0.01 %

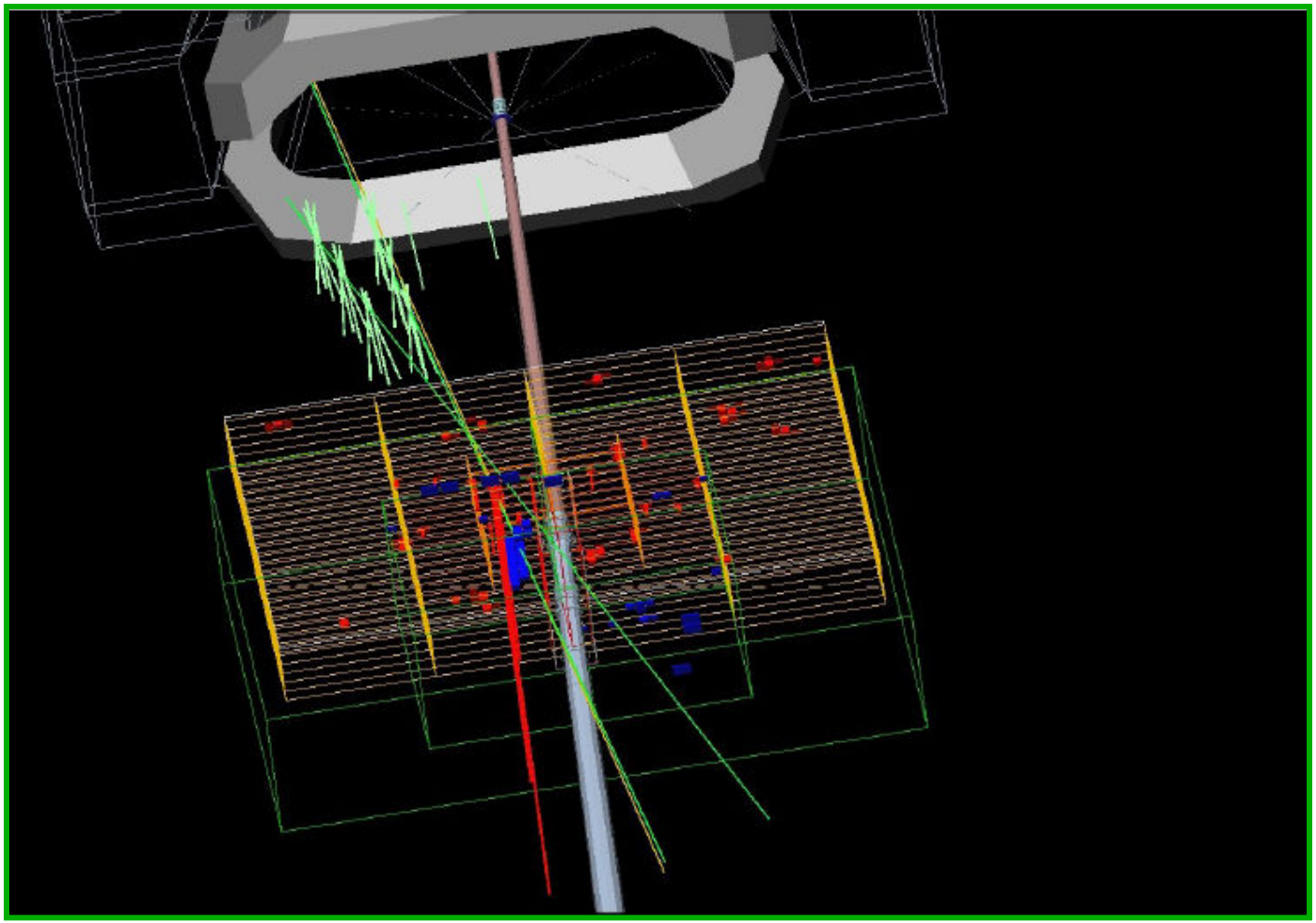
LHC Startup



After the LHC Media Day in September 2008…

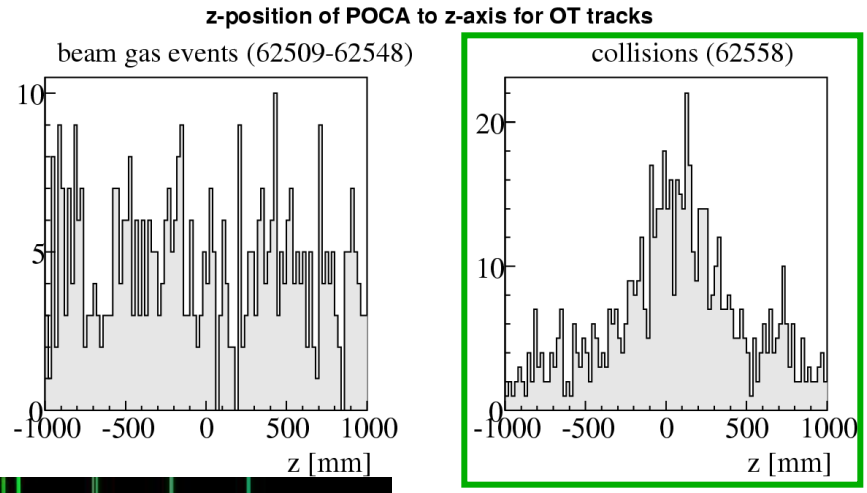
Cosmics

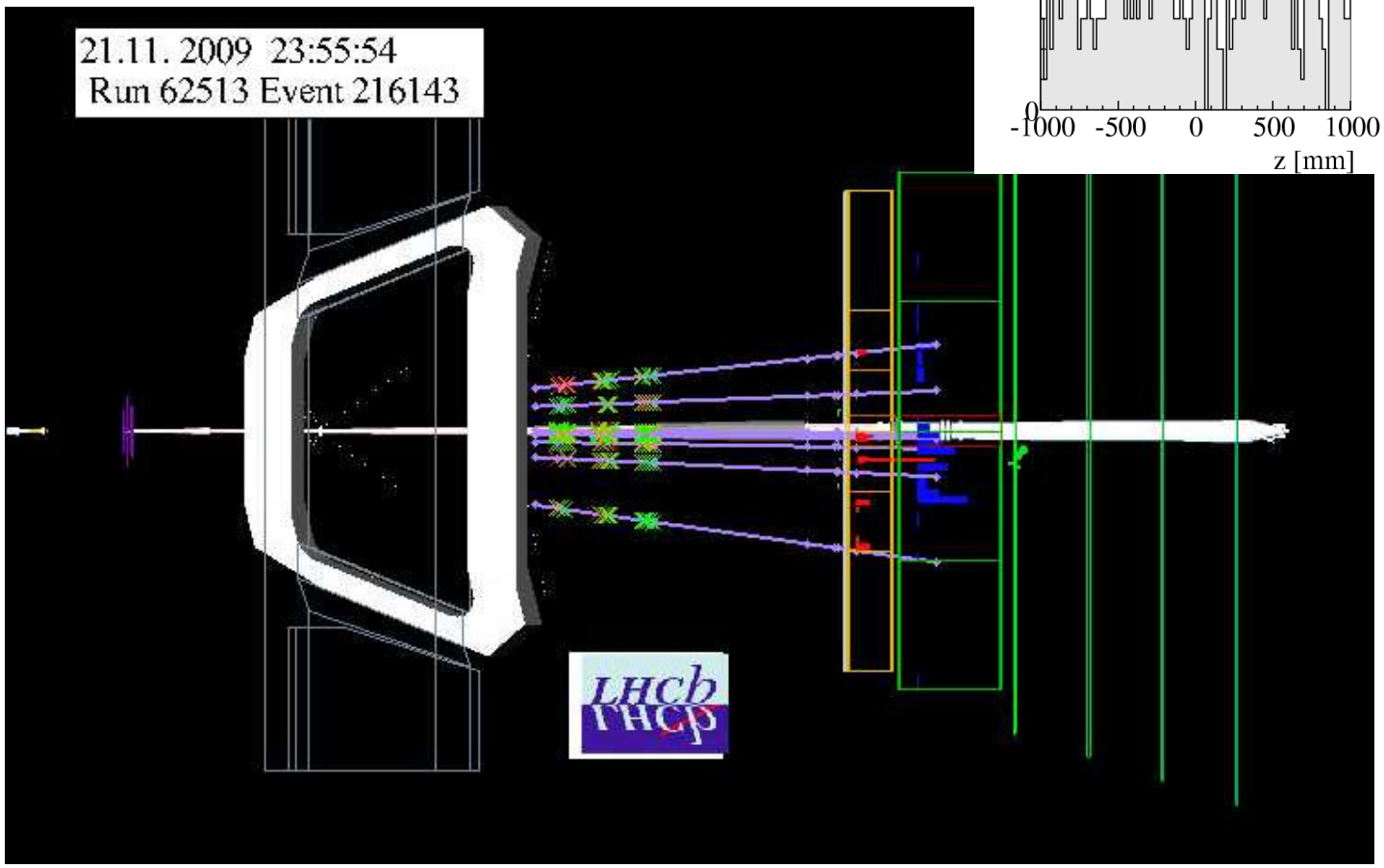
… we have taken lots of cosmics (timing, alignment, …)



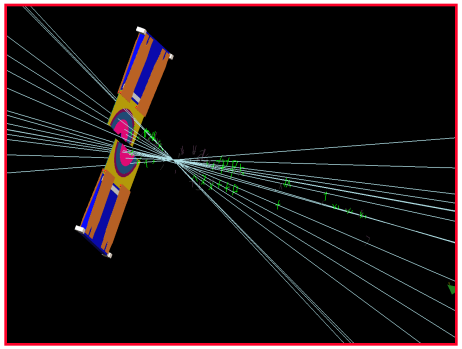
Beam Gas

… and then the first p-beamgas collisions…



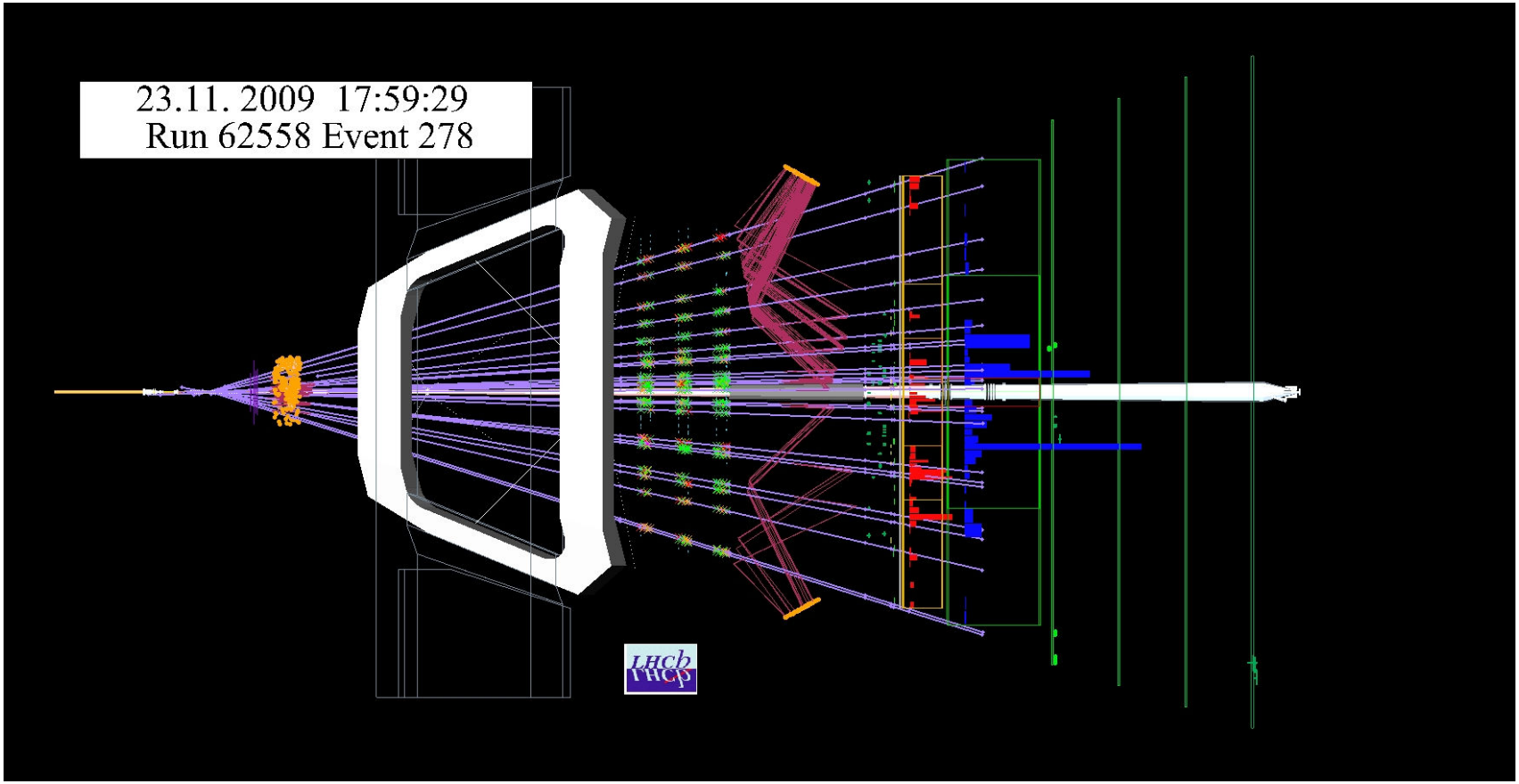


1st evidence of pp collisions before VELO went in!?



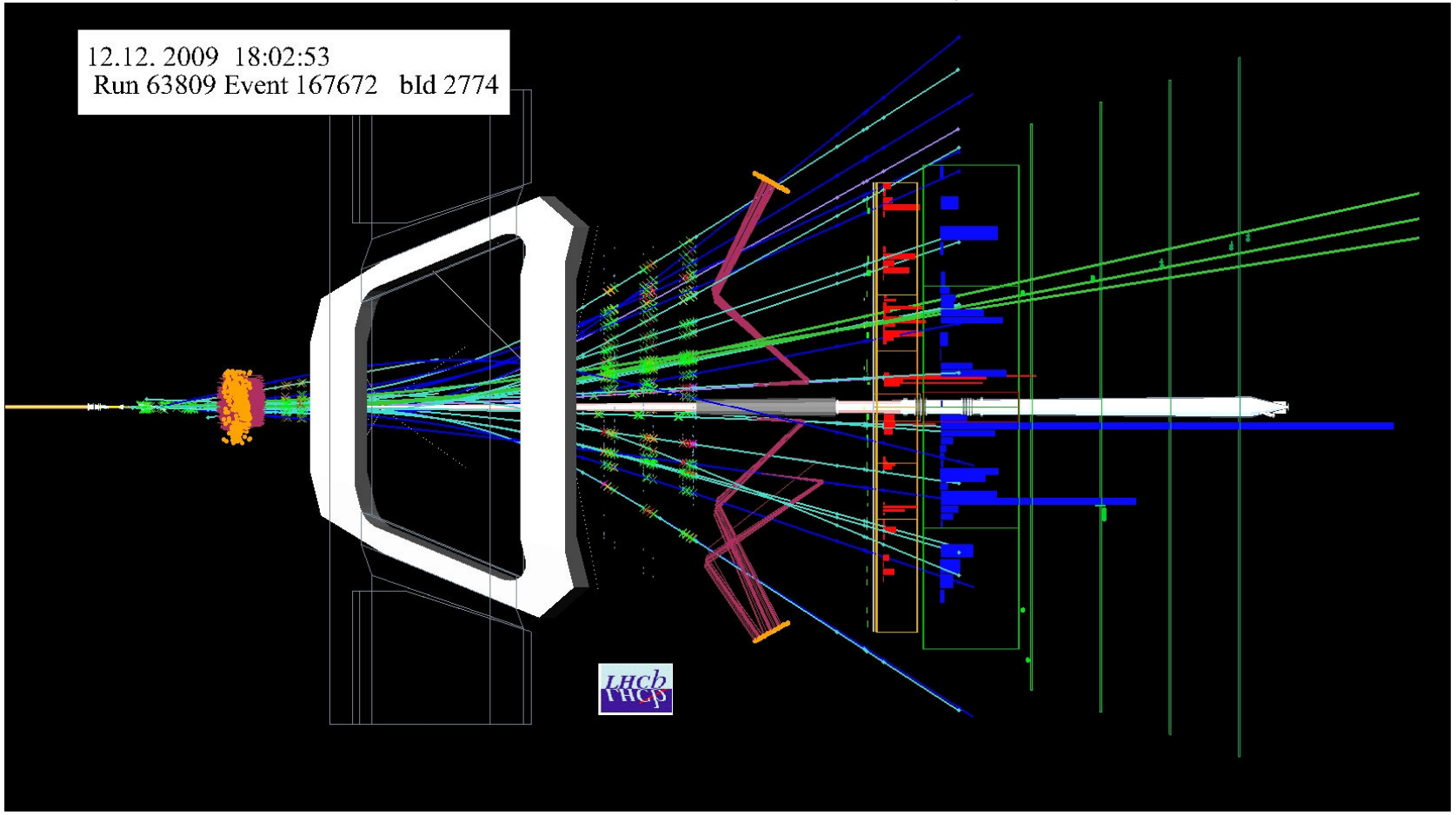
1st Beam Data

… and finally the first beam-beam collisions …



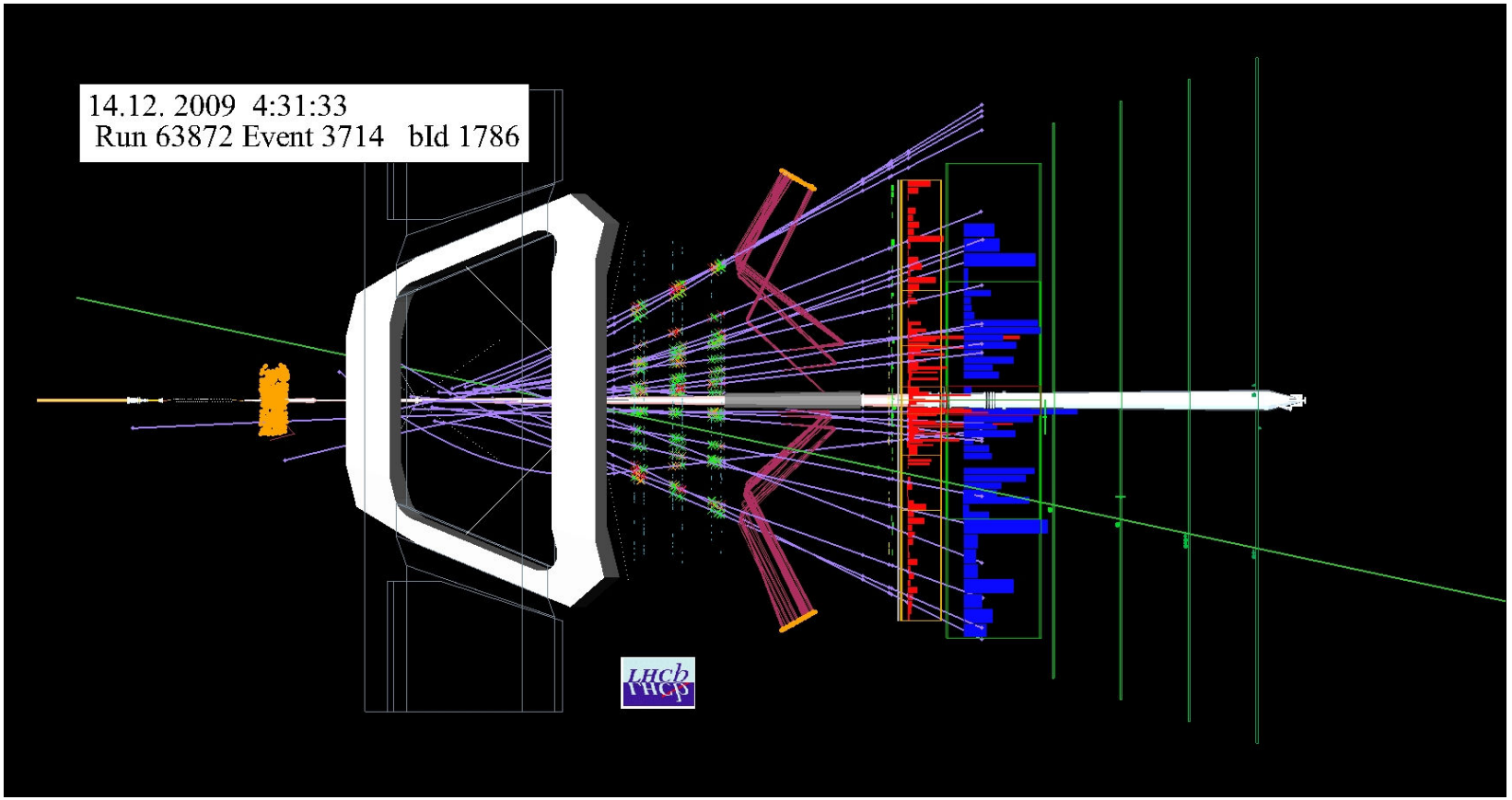
1st Beam Data (cont'd)

… and finally the first beam-beam collisions …



Beam Collisions at 2.4 TeV

… and at the end of the 2009 run, also some collisions at $\sqrt{s}$ = 2.4 TeV

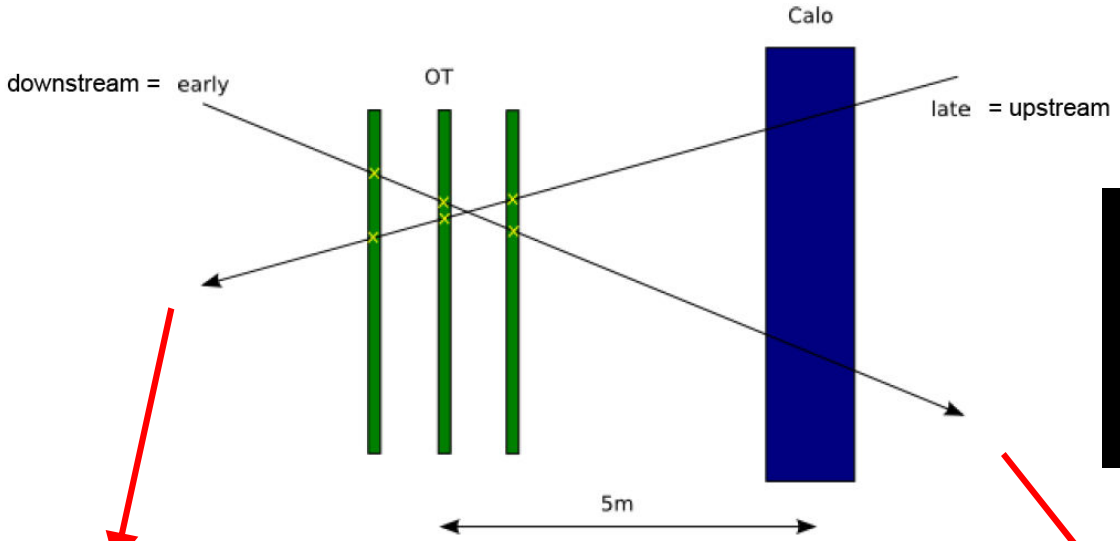


Data Analysis

Look at various type of data with various goals :

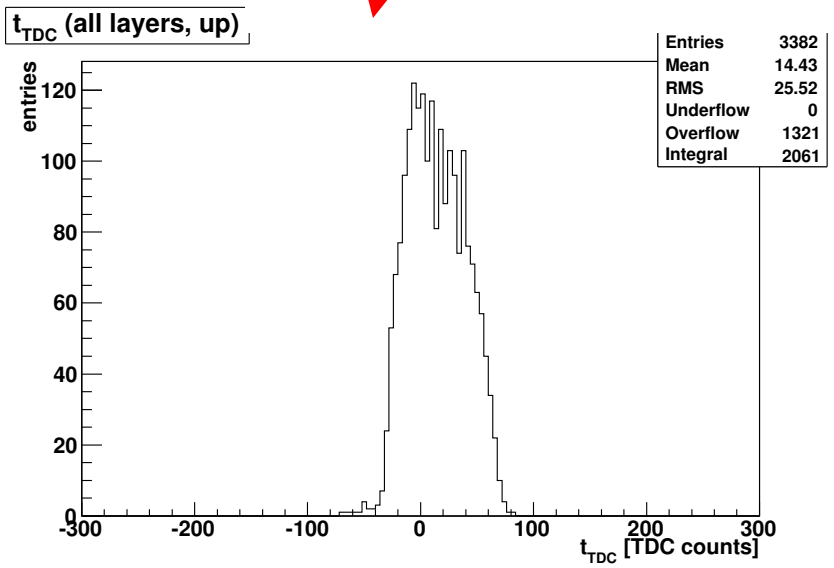
- *Random triggers (noise, debug FE : buffer overflow, mismatch,…)*
- *Calibration triggers (threshold scans, time-delay scans)*
- Cosmics triggers :
  - Detector geometry + channel mapping
  - Data decoding
  - Pattern recognition
  - Track fitting
  - RT calibration
  - T0 determination
  - Alignment
  - …
- pp collision data:
  - MC tuning
  - efficiencies
  - …
  - first invariant masses

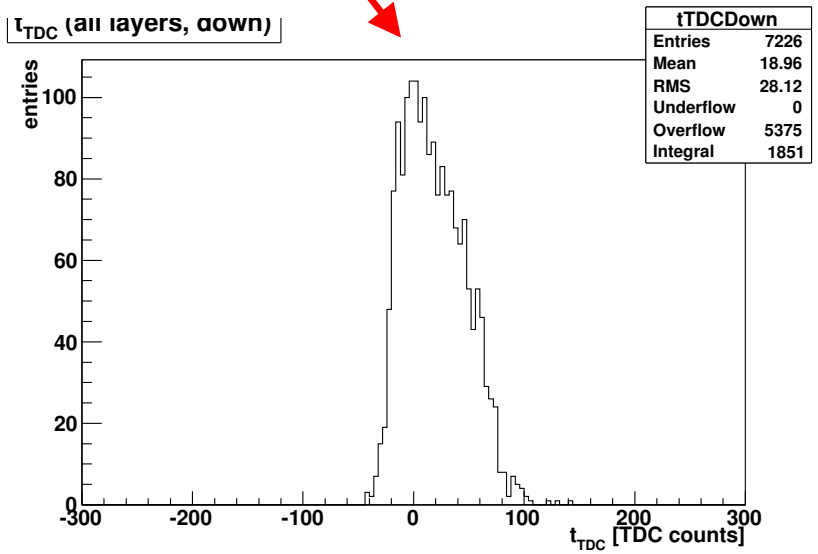
Cosmic Data



Correct for:

- Down/Up stream
- TOF
- Wire propagation

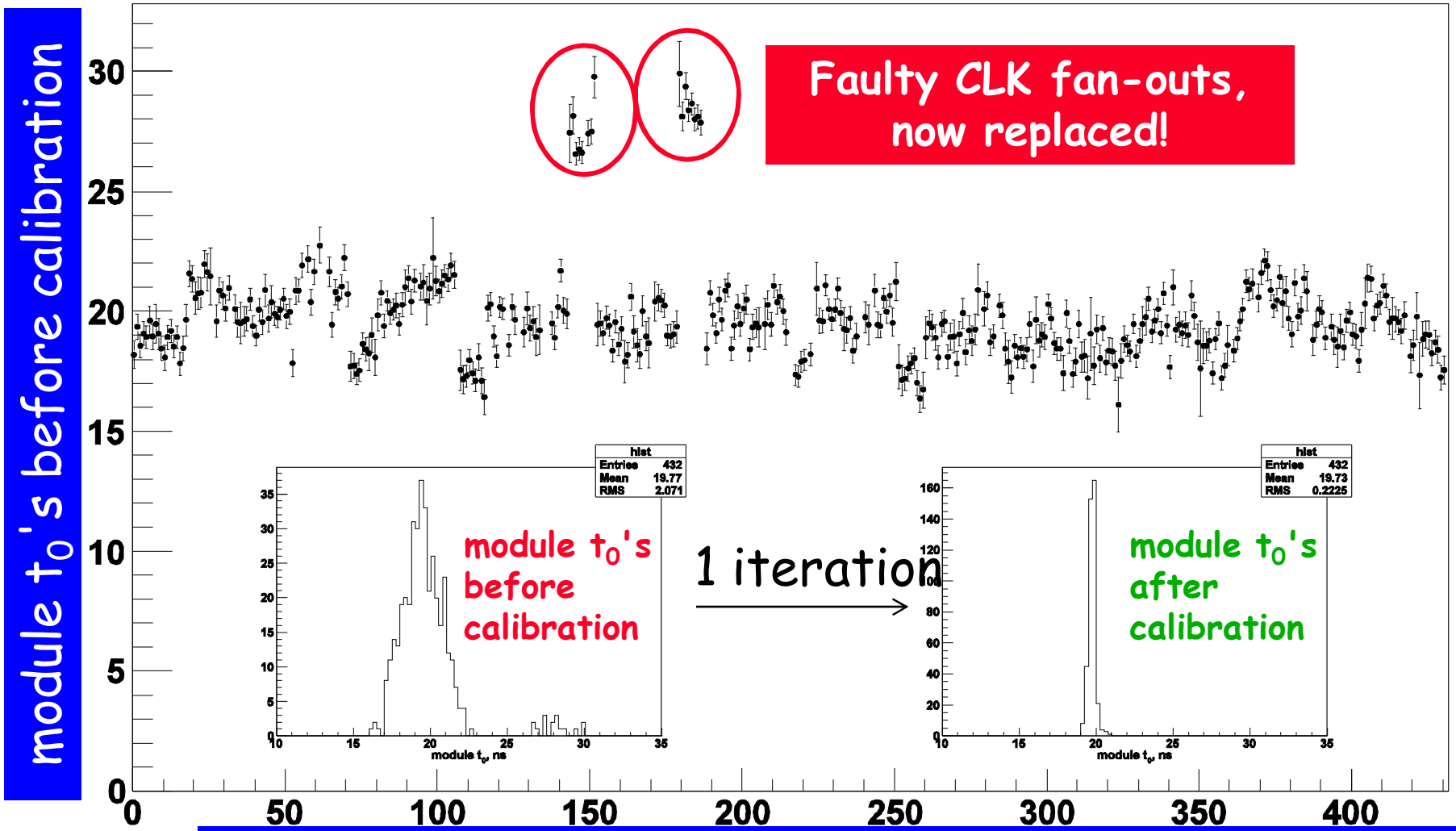




$$TDC = t_{cosmic} + t_{TOF} + t_{drift} + t_{prop} + t_0$$

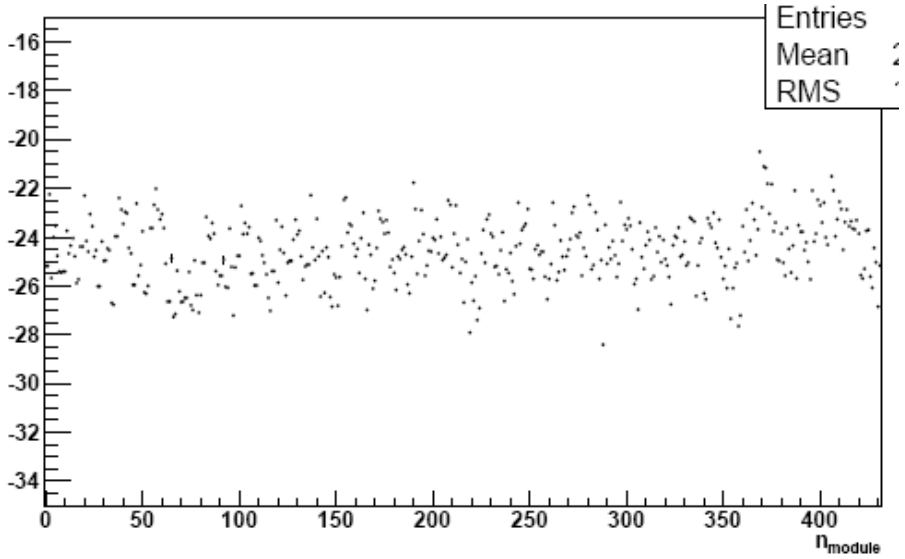
T_0 (1st iteration from 2009 Cosmics)

t_0 correction (σ = 1 ns) using average drift time per module

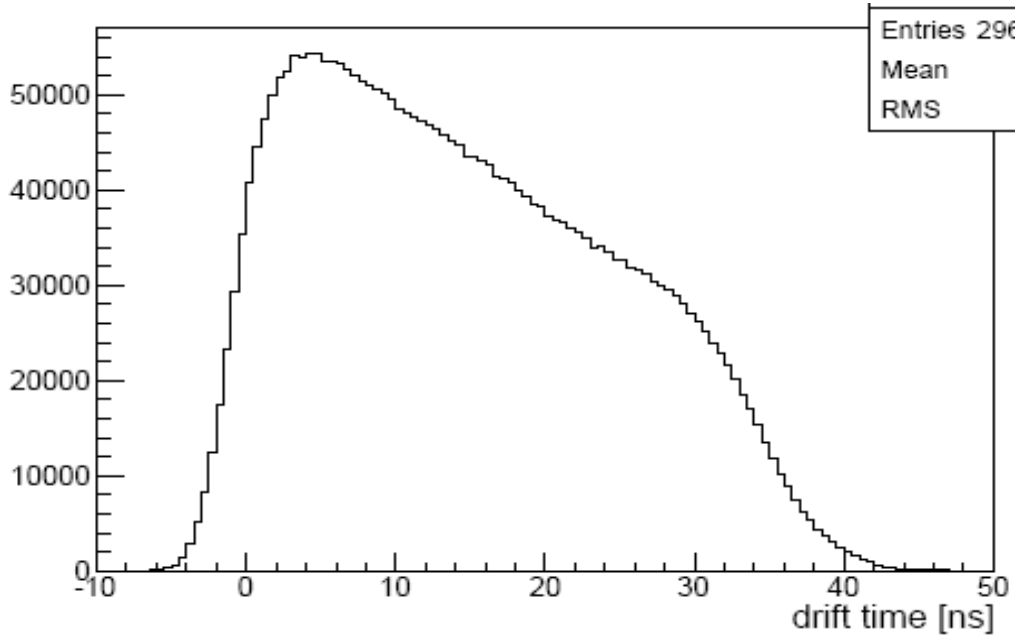


Drift Time

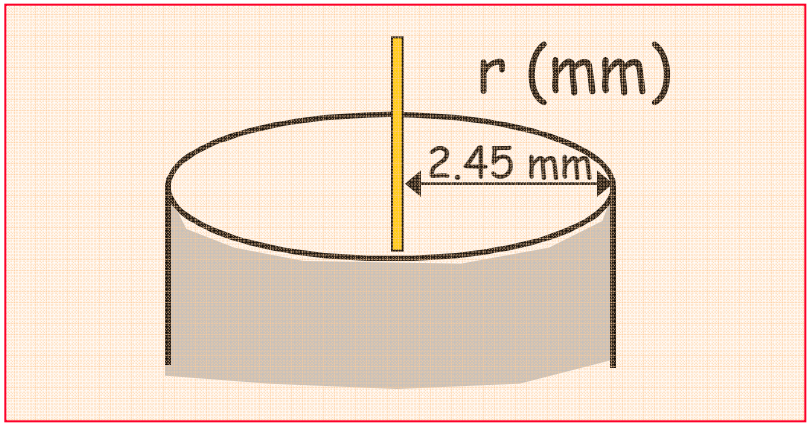
T_0 corrections (2010 Database)

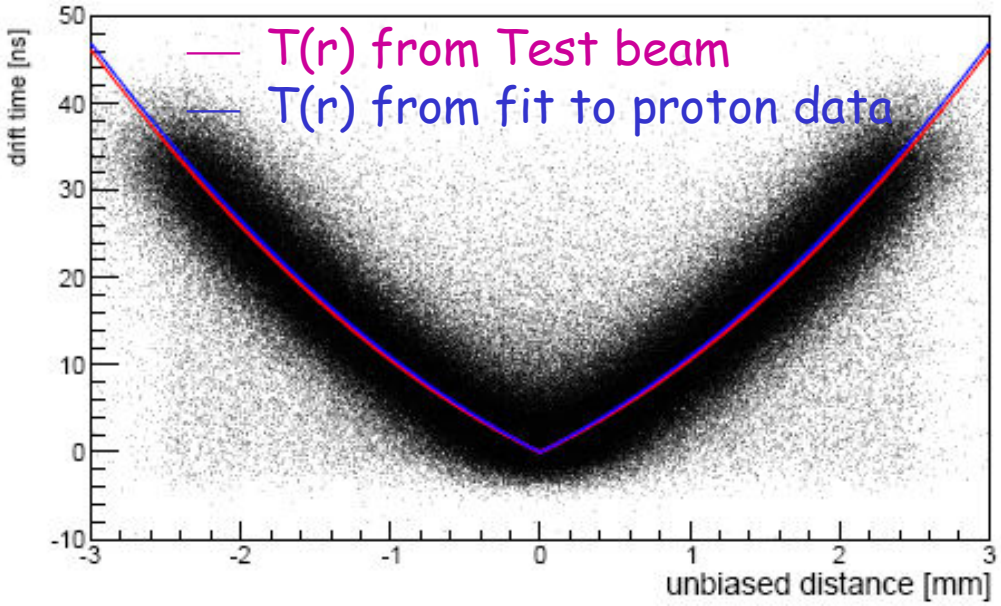


Corrected Drift Time (integrated over full OT)

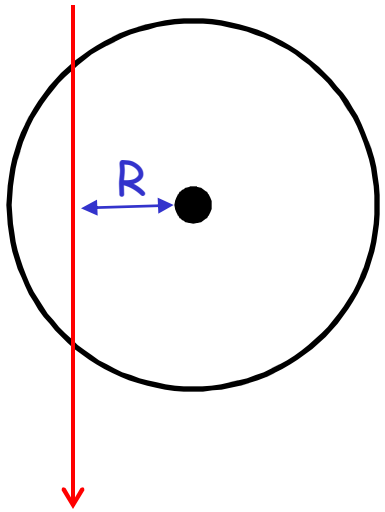


RT Relation



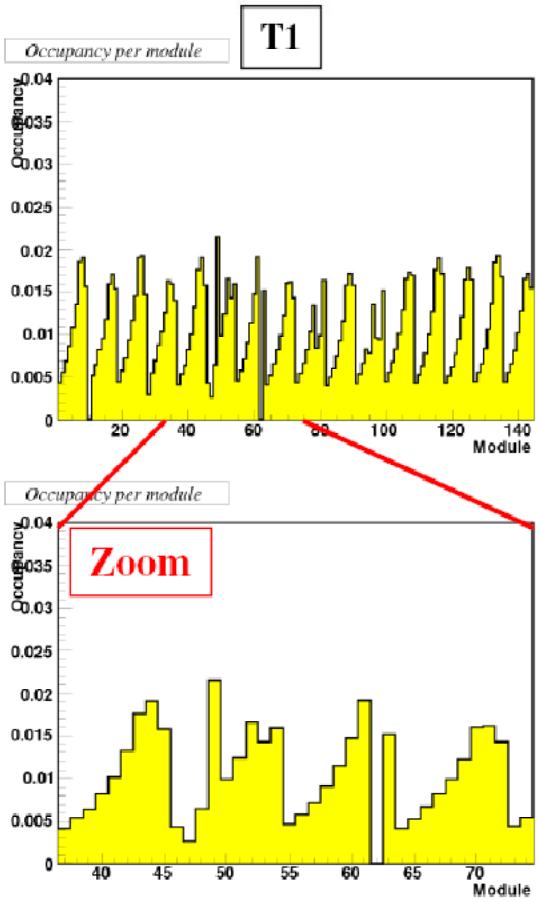


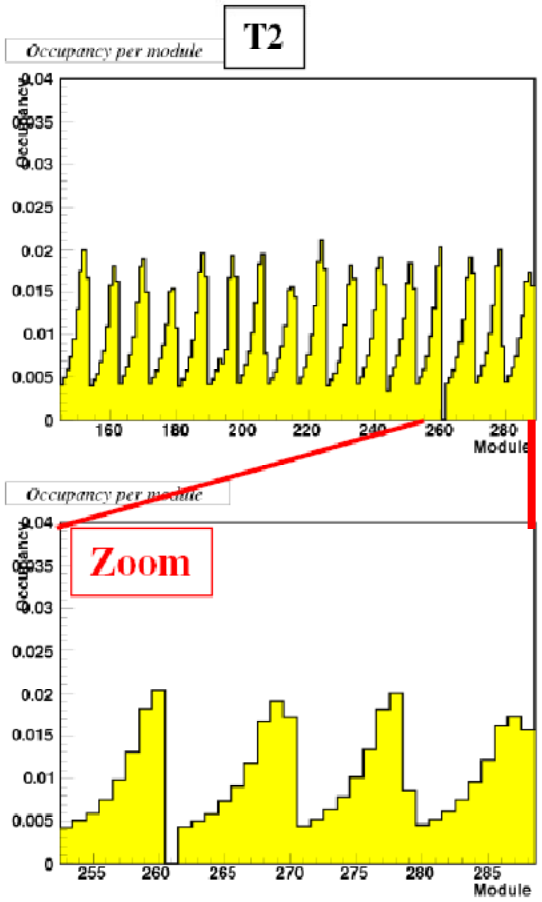
Dritft-time space relation T(r)

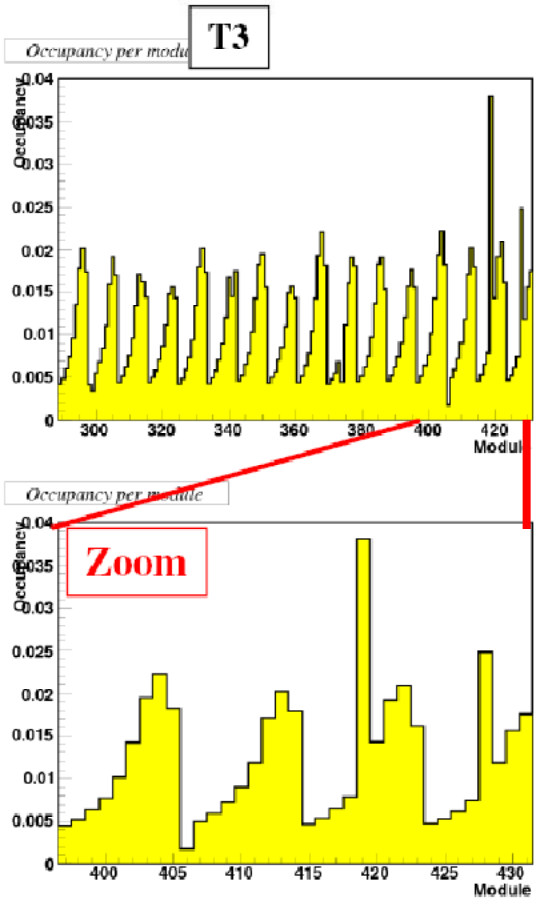


Occupancy

Occupancy distribution from 2009 pp collision as expected.
Few dead and noisy channels, all identified and repaired in 2010

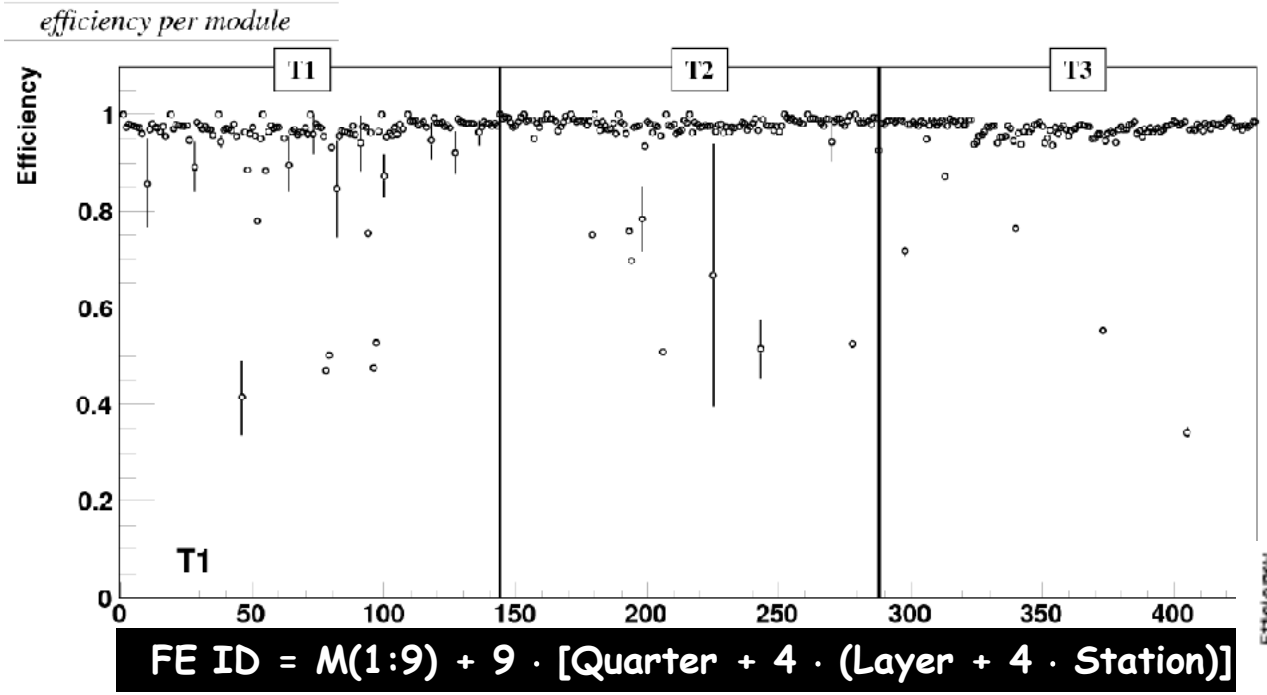




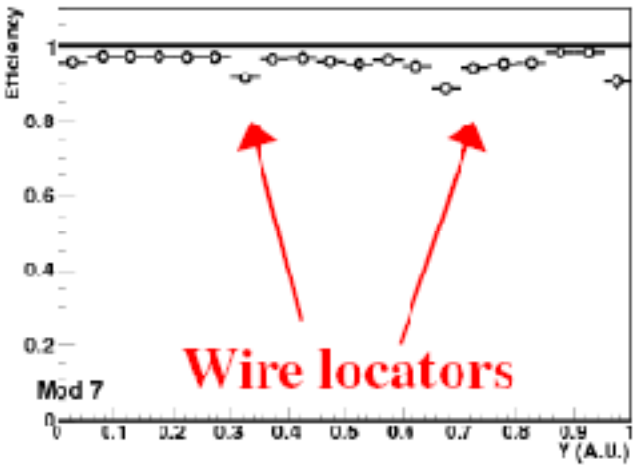


Efficiency Profiles

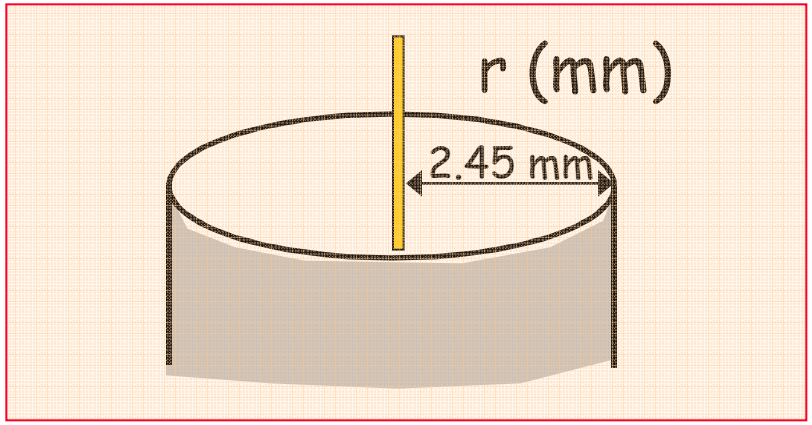
In 2009 pp collision data only a handful (<98%) not fully working: all identified and repaired in 2010

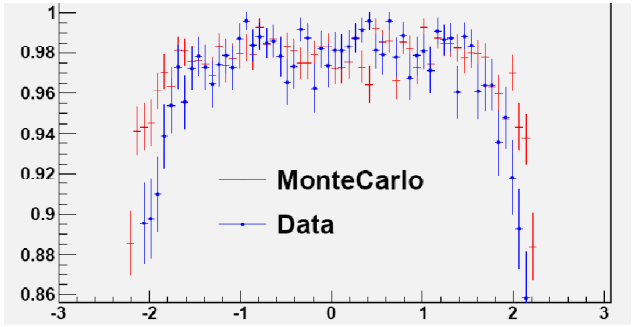


Y Profile

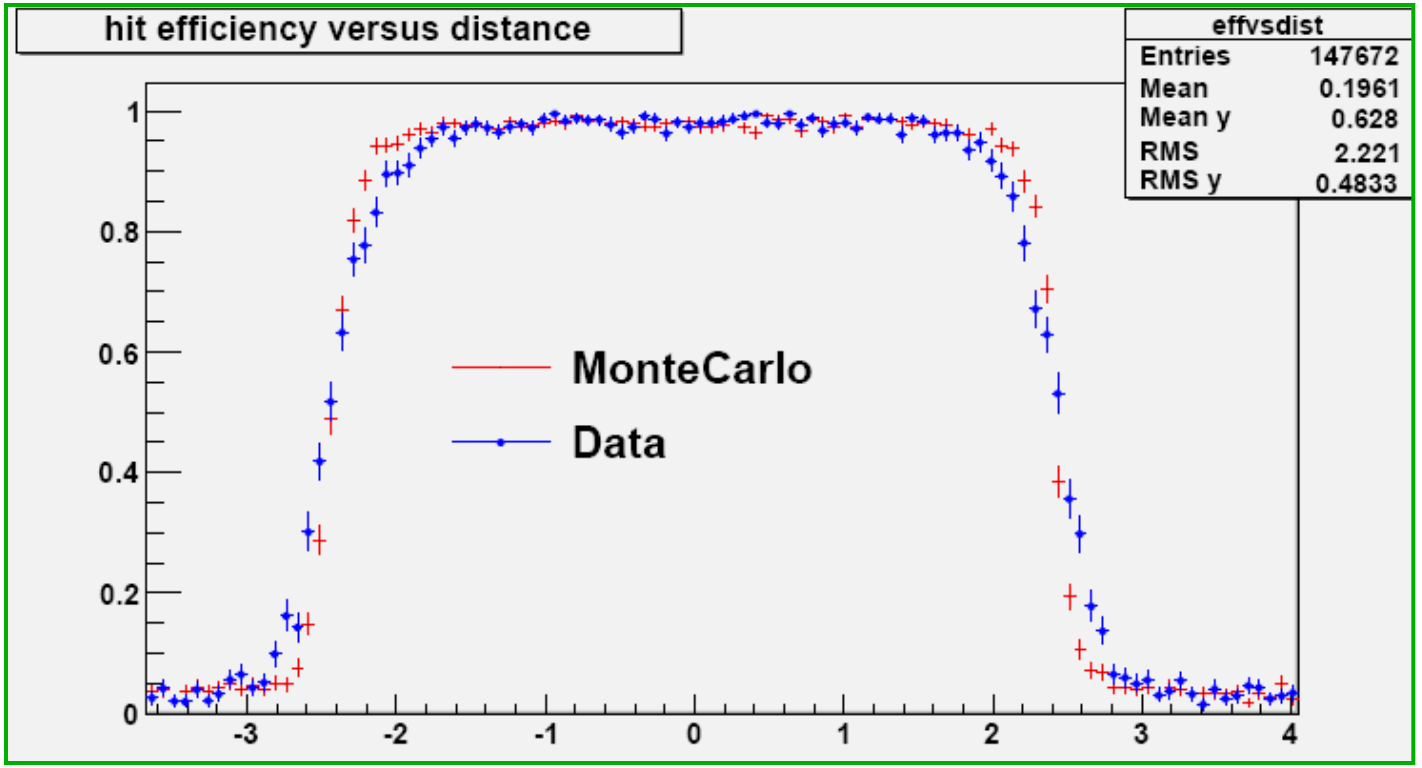


Drift Cell Efficiency

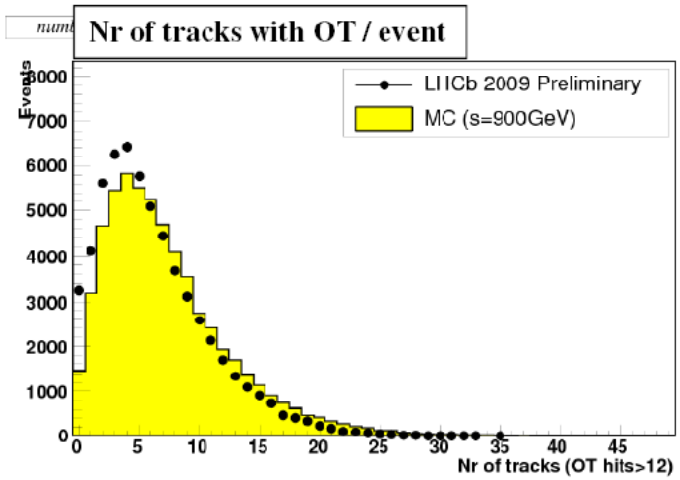


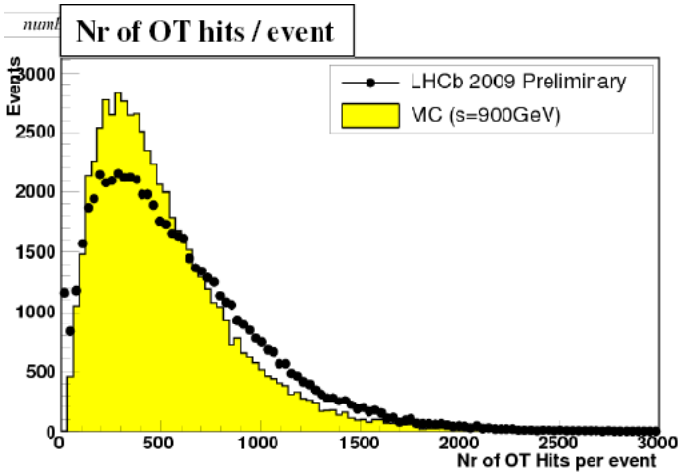


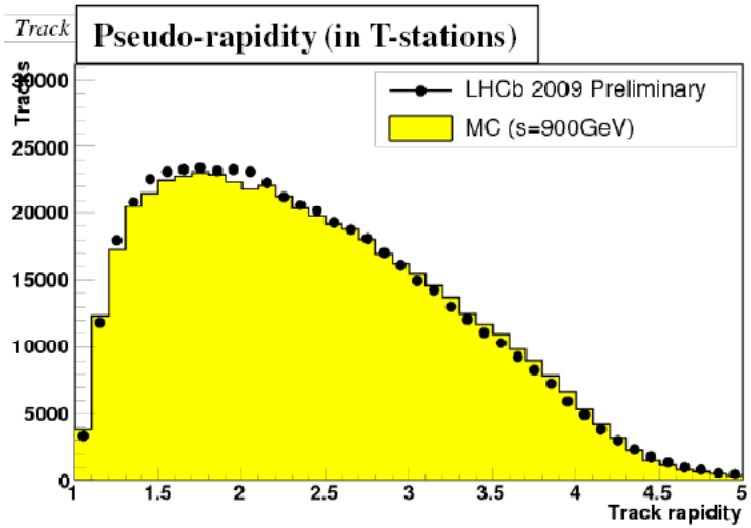
98.7% efficiency plateau

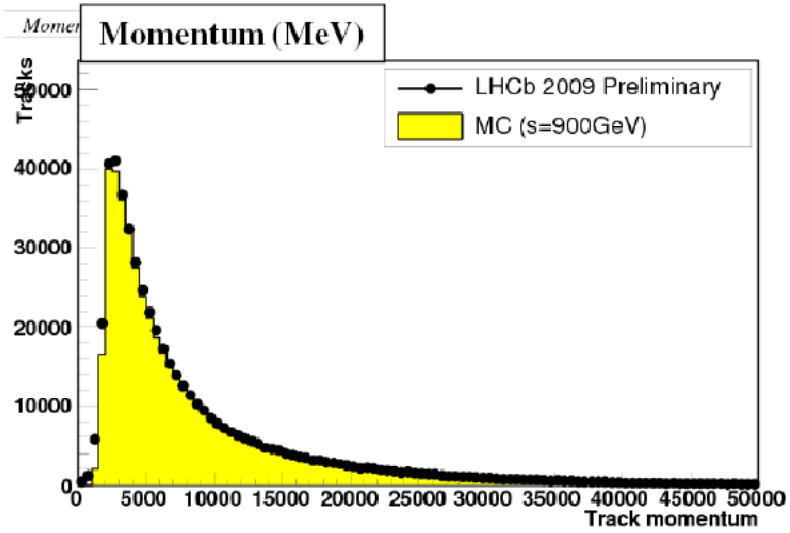


Track Distributions





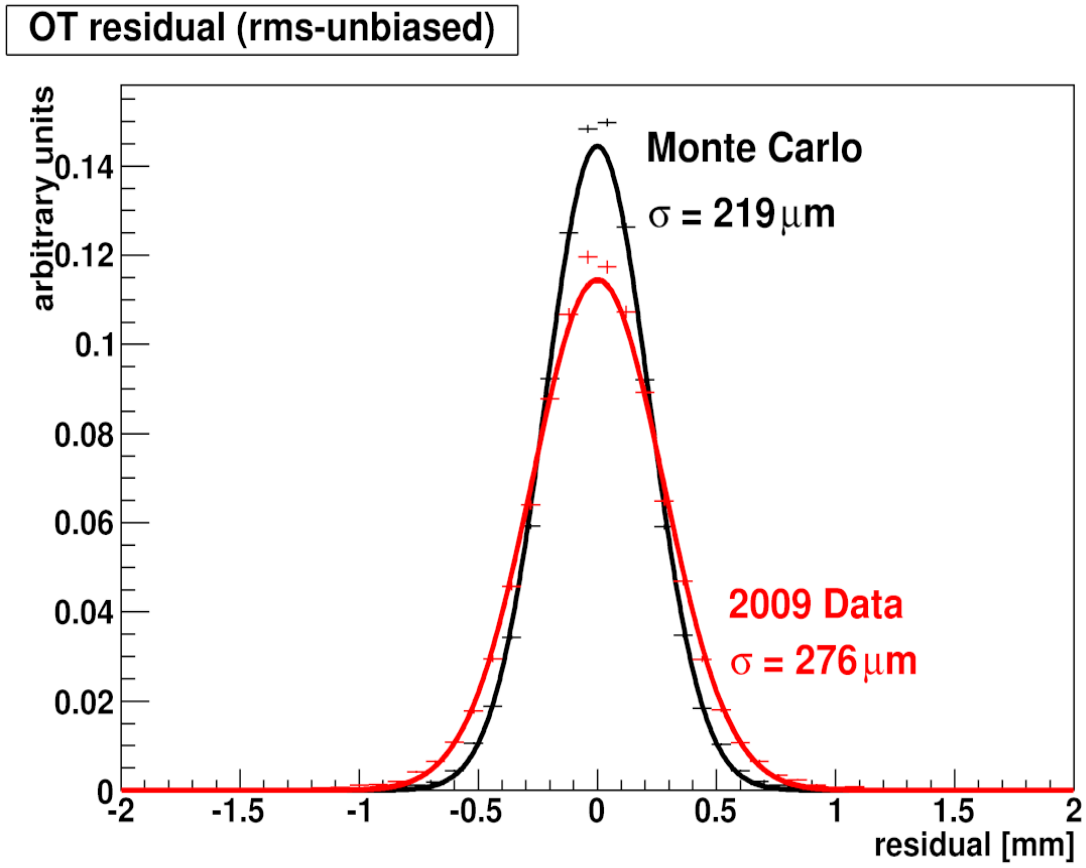




First look, roughly as expected
No beam gas correction applied

Resolution Studies

Residuals from Track Fitting procedure

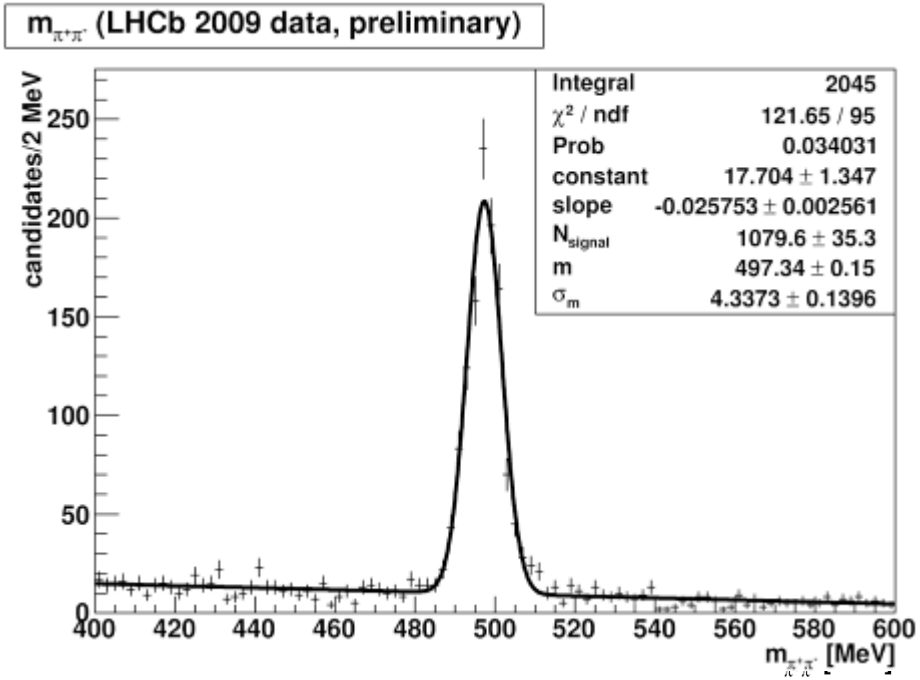


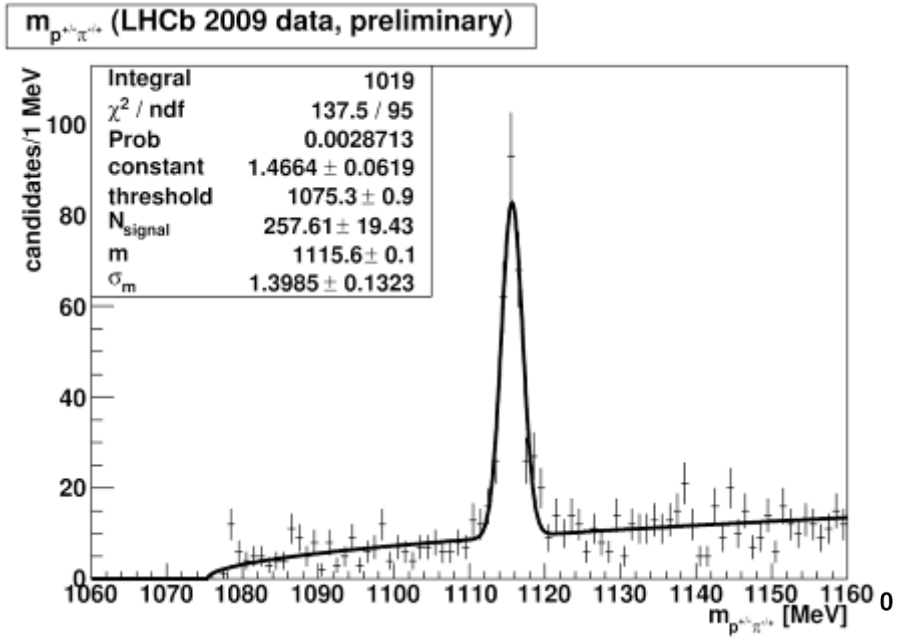
Discrepancy between data and MC will presumably vanish once we complete individual modules alignment

Residual distribution may be "biased" by outliar removal in pattern recognition and track fitting procedures

First Reconstructed Decays

Still enough to start looking at invariant masses…





σ	= 4.3 ± 0.1	MeV/c^2
M(Ks)	= 497.3 ± 0.2	MeV/c^2
M(Ks^{PDG})	= 497.7	MeV/c^2

σ	= 1.4 ± 0.1	MeV/c^2
M(Λ)	= 1115.6 ± 0.1	MeV/c^2
M(Λ^{PDG})	= 1115.7	MeV/c^2

Summary

- LHCb is eager to collect data with its full detector as LHC turns on to search for new physics by
  - testing the CKM matrix mechanism
  - probing rare decays

- Tracking system performance of crucial importance
  - Outer Tracker consisting of straw-tubes modules
  - All OT modules built and tested
    - Quality Assurance during production
    - Beam tests
    - Unexpected module ageing discovered, due to araldite plastifier

- All OT modules installed and re-tested in situ
  - Module ageing remains a concern
  - Commissioning completed
    - Electronics debugging
    - Cosmic data: track reconstruction, T_0 and RT calibration, alignment, etc.
    - Collision data: occupancy, efficiency, resolution, etc.